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BIOMECHANICAL ANALYSIS OF MILITARY BOOTS: PHASE II

VOLUME I

Human User Testing of Military and Commercial Footwear

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13. ABSTRACT *(Maximum 200 words)*

This is a two-volume report on human user testing of military and commercially available footwear. Volume I, NATICK/TR-96/011, contains the body of the report, and references; Volume II, NATICK/TR-96/012, contains the appendices comprised principally of summary statistics. The military footwear tested consisted of the black leather combat boot and the hot weather boot; the commercial items were a basketball shoe, cross trainer, hiking boot and work boot. Men and women performed the following activities in a laboratory setting while wearing each footwear type: walking, marching, running, jumping from heights and running an agility course. The data acquired included ground reaction forces, in-shoe pressures, sagittal plane kinematics, rearfoot movement, leg muscle activity, metabolic rate, and heart rate. The results indicated that the magnitudes of vertical ground reaction forces were lowest with the basketball shoe and the cross trainer. The military and the work boots were associated with lowest amounts of ankle dorsiflexion and the greatest degrees of flexion at the metatarsal-phalangeal joints. The fastest times to completion of the agility course were achieved with the basketball shoe and the cross trainer. The third report in this series is "Biomechanical Analysis of Military Boots: Phase III Recommendations for Design of Future Military Boots," NATICK/TR-96-013. Phase I is "Biomechanical Analysis of Military Boots: Materials Testing of Military and Commercial Footwear," NATICK/TR-93/006.

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PREFACE

This final report for Phase II of the biomechanical analysis of military boots and other footwear was prepared under U.S. Army Soldier Systems Command, Natick Research, Development and Engineering Center contract DAAK60-91-C-0102. The work was performed at the Biomechanics Laboratory, Department of Exercise Science, University of Massachusetts, Amherst, MA. The project officer for the contract was Dr. Carolyn K. Bensel. Dr. Bensel is affiliated with the Behavioral Sciences Division, Science and Technology Directorate. This project is part of the 6.2 program 1L162723AH98AAKOO (Aggregate Code T/B1368) -- Biomechanical Approach to Soldier-CIE Integration, which is being carried out by Dr. Bensel and other members of the Behavioral Sciences Division.

This report for Phase II is in two volumes. Volume I (NATICK/TR-96/011) contains the body of the report, including references; Volume II (NATICK/TR-96/012) contains the appendices, which are comprised principally of summary statistics. The references for the other reports in the series are:

Hamill, J. and Bensel, C. K. (1992). *Biomechanical analysis of military boots. Phase I: Materials testing of military and commercial footwear* (Tech. Rep. NATICK/TR-93/006). Natick, MA: U.S. Army Natick Research, Development and Engineering Center.

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BIOMECHANICAL ANALYSIS OF MILITARY BOOTS
Phase II: Human User Testing of Military and Commercial Footwear

INTRODUCTION

The most widely issued footwear in the Army and the Marine Corps is a boot designated for use in training, garrison, and field environments when specialized footwear (e.g., safety shoes, cold weather boots, hot weather boots) is not needed. Male and female recruits receive this boot at the beginning of their basic military training and use it for almost all activities that comprise "boot camp". Recruits are sometimes permitted to wear commercial sport shoes, which they bring with them from home or purchase after arriving for training. The sport shoes are worn only to a limited extent, generally for portions of the formal physical training program, such as daily calisthenics and runs, although these activities may also be performed in the boot. After completing basic training, military men and women continue to wear the boot for physical training, field exercises, in their garrison work environments, and on the battlefield.

There have been a number of generations of this footwear, each differing from the others in design and material composition. The latest version was introduced into the military inventory in the mid-1980s. This boot, commonly referred to as the "combat boot", has a leather upper. The outsole is direct molded to the upper and has a deep lug design. The boot is issued with a removable, urethane foam insert that has a fiberboard backing and extends from the heel to the toe of the boot.

Development of the latest combat boot began in the early 1980s at the U.S. Army Natick Research, Development and Engineering Center. The development effort was guided by requirements, or performance criteria, that were generated by Army and Marine Corps organizations responsible for identifying the characteristics that materiel must embody to meet the needs of military personnel. The military wanted a boot that enhanced the locomotor capabilities of the wearer, minimized the occurrence of lower extremity problems, and was comfortable. Other requirements pertained to weight, height, design of the closures, camouflage characteristics, water-resistance, durability, storage life, military appearance, and outsole composition. Still other requirements dealt with cost of the item, production rate, and production capabilities within the United States. Indeed, much was demanded of the footwear, and the boot reflects the attempt to accommodate a range of requirements at a relatively low cost.

In addition to the combat boot, there is another boot that is frequently worn by many Army and Marine Corps personnel, although this boot is not as widely used as the combat boot. The second footwear item, which was developed during the 1960s for use in Southeast Asia, is commonly referred to as the "jungle boot". This boot is now prescribed for use in hot-humid climates, but soldiers are given the option of wearing it in other climates should they so choose. Like the combat boot, it is worn for physical training, field exercises, in garrison, and on the battlefield. The jungle boot is fabricated of leather in the foot portion and has a cotton/nylon duck upper. The boot has a direct molded sole with a lug tread and a steel plate incorporated into the insole. Like the combat boot, the jungle boot is issued with a removable insert. As was the case with the combat boot, development of the jungle boot was guided by requirements of the military users. For example, the upper is made of duck because of a requirement for the boot to dry quickly; eyelets are in the arch area because some means for water to drain out of the boot was required; and the steel plate serves a requirement for protection of the foot from puncture by spikes embedded in the ground.

The growing interest of the public in physical fitness over the last 15 to 20 years, and the attention paid by footwear manufacturers to this expanding market, has stimulated research into materials and construction processes for athletic footwear. Much of this research has been in the realm of sport biomechanics (Cavanagh, 1980; Nigg, 1986b). Goals of the biomechanics research done on athletic footwear include enhancing the locomotor performance of the wearer and reducing the incidence of lower extremity injuries (Cavanagh, 1980; Nigg, 1986b). There is evidence that progress has been made in achieving these goals (Cavanagh, 1980; Nigg, 1986a). Although the military services also have an interest in enhancing the locomotor performance of personnel and reducing lower extremity injuries (Bensel, 1976; Bensel and Kish, 1983), findings from biomechanical studies have not yet been systematically employed in the development of military boots.

One outcome of the public's focus on physical fitness, and the footwear industry's responses to it, is that the consumer is faced with a wide selection of shoes for just about every popular athletic activity. The industry has stressed specificity in shoe design. That is, use of a specific type of footwear for a specific activity. The situation in the civilian sphere, stressing specificity, is unlike that in the military; a single type of military footwear, such as the combat or the jungle boot, must be appropriate to wear for a wide variety of activities (e.g., running, climbing, crawling, marching, jumping) on a wide range of surfaces and terrains. In addition, as discussed above, there are many considerations influencing the design of military boots that are not germane to footwear for civilian uses.

In spite of the differences between military and civilian applications in terms of demands placed upon footwear, the goals of enhancing the wearer's performance and reducing lower extremity injuries are vitally important in both domains. Insofar as it leads to achieving these goals, biomechanics can contribute to development of military footwear, as it has to development of footwear for the civilian market. However, biomechanics has not had a role in military footwear research; it appears that biomechanical testing was performed on military footwear only once. The work was conducted in the early 1980s by deMoya (1982) and involved a predecessor to the present combat boot.

Given the lack of information about the biomechanical properties of current military boots and the potential for improving the boots in the future through application of biomechanical principles, a research program focusing on the biomechanical analysis of military footwear was established. The objective of the research was to develop a series of recommendations for future military footwear with regard to materials, design, construction, fabrication techniques, and any other features that would benefit the performance and the lower extremity health of military personnel, particularly ground troops. The research was divided into two phases, with the first phase consisting of materials testing and the second human user testing.

The question has been raised in the biomechanical community as to whether materials tests yield data that relate to the functioning of individuals performing in the footwear (Bates, 1985). The human/footwear system is a complex biomechanical unit with performance characteristics that may be unique to an individual, whereas materials tests assume a commonality across individuals' functional needs. However, materials tests are more reliable, less time-consuming, and less costly than testing of footwear on humans (Cavanagh, 1980; Nigg, 1986b). There is general agreement that materials tests alone are inappropriate but serve an important purpose when complemented by human testing (Cavanagh, 1980; Frederick, Clarke, and Hamill, 1984; Nigg, 1986b). Used in this manner, materials testing can be a screening device to identify, out of a larger array of footwear items, those particular items embodying features worthy of further study in human testing. Also, the physical characteristics of a footwear item are specified through materials tests. This information is needed to understand the results of human user tests of the item and to convert the results into improvements in the item.

The approach taken in the present research program was to complete the materials testing prior to initiation of human user testing. The materials testing was carried out on eight types of footwear. Funding and time constraints dictated that only six types be tested in the user phase of this research; the findings from the materials testing were used to determine which footwear types would undergo further study in user testing.

The footwear items included in the first phase of the research were two types of military boots, the combat and the jungle boots, and six types of commercial sport shoes and work boots. The combat and the jungle boots were selected for study because they are general-purpose footwear items and are widely used throughout the Army and the Marine Corps. The same military boots were included in the user testing, along with four of the six commercial items used in the first phase.

The commercially available items under study were not developed for use as military field footwear. However, they do incorporate materials and design concepts that, if proven to be beneficial to the performance and the lower extremity health of the wearer, could be adapted to a military boot. Thus, the commercial items were included in this study in order to acquire information on their performance characteristics. The testing of the commercially available footwear also served to generate data against which to assess the findings for the military footwear.

The results of the second phase of the research effort, the human user testing, are reported here. The results of the first phase of the research, the materials testing phase, were reported earlier by Hamill and Bensel (1992).

Materials Testing of Military and Commercial Footwear

The six types of commercial footwear items studied by Hamill and Bensel (1992) in the materials testing phase were: the Nike Air Max, a Nike cross trainer, a Red Wing work boot, the Reebok Pump, a Rockport hiking boot, and a Rockport walking shoe. These commercial footwear items, along with the combat and the jungle boots, were subjected to tests of forefoot flexibility, rearfoot stability, outsole wear, water penetration, outsole friction, and impact. Testing of forefoot flexibility with the uppers in place revealed that the combat and the jungle boots were less flexible than all commercial items except the Red Wing work boot. The military boots and the Red Wing work boot had the highest scores on the rearfoot stability test, indicating high medial and lateral stability. On the sole wear test, the combat boot, the Red Wing work boot, and the Rockport walking shoe had the poorest scores; the Nike Air Max and the Reebok Pump had the best. The interiors of the combat boot and the other footwear types with all-leather uppers remained dry during the 15-min immersion period on the water penetration test. The two types of footwear that had cloth in the uppers, the jungle boot and the Nike Air Max, did not. The jungle boots were retested after the eyelets set in the leather in the arch area had been plugged. Under this condition, water did not penetrate into the jungle boot during the immersion period. With regard to frictional characteristics of the outsoles on various surfaces, no one footwear type was vastly superior or vastly inferior to the others (Hamill and Bensel, 1992).

Hamill and Bensel (1992) found that the impact test revealed the greatest differences between the military and the commercial items. The best overall findings on this test were associated with the Nike Air Max and the Nike cross trainer. These shoes reduced the peak g and the peak pressure by approximately 50% compared with the military boots. The Air Max and the cross trainer also reduced peak g and peak pressure by some 30% to 40% compared with the Red Wing work boot, the commercial item that had impact characteristics most similar to those of the military boots. Furthermore, longer times to peak g were obtained with the Air Max and the cross trainer than with the military boots and the Red Wing. In addition, the Nike cross trainer had particularly high values for coefficient of restitution and energy return, two more parameters of the impact test, compared with the values for the military boots.

As was mentioned above, two items studied in the materials testing phase were not included in the human user testing phase of this research. The Nike Air Max was one of these. It yielded results on the impact test that were similar to those for the Nike cross trainer. In addition, the height of the cross trainer, measured from the heel breast to the top of the upper, is greater than the height of the Air Max and more closely approximates the height of a boot upper. Therefore, the Nike cross trainer was selected for further testing and the Nike Air Max was not. The Rockport walking shoe was the other commercial item that was tested in the first phase of this research, but not in the second. This walking shoe was not selected because, aside from poor abrasion resistance on the outsole wear test, the shoe did not evidence particularly good or bad performance characteristics. Also, like the Nike Air Max, the Rockport walking shoe has a low upper compared with the other military and commercial footwear items included in this research.

The six types of footwear that were selected for the human user testing had uppers that extended to the level of the lateral malleolus or higher. These "high-top" designs tied together the actions of the lower leg, the ankle, and the foot. Thus, the uppers on the footwear items served similar functions.

Measures Employed in Human User Testing

Both men and women participated in the user testing. They wore the two types of military boots and the four types of commercial footwear while performing a number of physical activities in a laboratory. The activities performed by the participants included walking, marching, and running. These movements were performed overground to generate kinetic, kinematic, and electromyographic (EMG) data and on a treadmill to generate metabolic and heart rate data. Movements were performed at the same pace overground and on the treadmill. However, the duration of the movements differed. Movement overground required seconds to complete. On the treadmill, a movement was performed continuously for 7 min in order to generate steady-state metabolic and heart rate data (Stainsby and Barclay, 1970).

The kinetic data acquired during overground walking, marching, and running consisted of ground reaction force-time histories as measured with a force platform. Ground reaction is the force in reaction to the push transmitted to the ground by the foot during ground contact. It reflects the acceleration of the total body center of gravity (Miller, 1990). During the locomotor movements in this study, forces were recorded throughout a contact, or support, phase. That is, recording began at the time of foot strike, or initial contact of the foot with the ground, and continued through toe-off, or termination of contact of the foot with the ground. The three force components measured were vertical force, antero-posterior force, and medio-lateral force.

Of the three force components, the vertical ground reaction force has been found to be the largest in magnitude during such locomotor movements as walking, marching, and running (Cavanagh and Lafortune, 1980). Research has shown that the amplitude of vertical ground reaction force increases with increases in speed (Munro, Miller, and Fuglevand, 1987). The amplitude of vertical ground reaction force during running is up to twice that occurring during walking (Cavanagh and Lafortune, 1980). Furthermore, the magnitudes of the vertical forces during running are quite high. Cavanagh and Lafortune (1980) reported vertical forces of two to three times body weight at running speeds in the range of 4.12 m/s to 4.87 m/s.

Cavanagh and Lafortune (1980) analyzed vertical force-time curves as a function of the center of pressure pattern of a runner's shoe at the time of first contact between the foot and the ground. On this basis, Cavanagh and Lafortune (1980) divided their subjects into two groups. One group, rearfoot strikers, was comprised of the runners whose first contact with the ground was made in the rear one-third of the shoe and the other group, midfoot strikers, was comprised of the runners whose first contact with the ground was made in the middle one-third of the shoe. The vertical ground reaction force of the rearfoot strikers showed a double peaked curve. The first peak (termed the impact peak because it is an impulsive force resulting from the impact of the foot and the ground) rose to approximately 2.2 times body weight within 23 ms of foot strike. The second peak (referred to as the thrust or propulsive peak because it occurs when force is being applied to the ground to propel the body into the next step) rose more slowly to about 2.8 times body weight within 83 ms of foot strike. The vertical force-time curve of the midfoot strikers did not reveal the initial peak; the force-time curve rose directly to the thrust peak, which averaged 2.7 times body weight and occurred at approximately 75 ms after foot strike.

Accelerometers attached directly to a bone or to the skin overlying a bone have been used by some researchers to evaluate the magnitude of forces that are generated within the skeleton during contact of the foot with the ground, particularly at foot strike (Light, MacLellan, and Klenerman, 1980; Valiant, 1990; Voloshin and Wosk, 1981). These methods capture the shock waves traveling in the bone at foot strike, information that cannot be resolved using a force platform because of the energy absorbing capacity of body tissues (Dickinson, Cook, and Leinhardt, 1985; MacLellan, 1984). It has been found that the internal forces can be multiples of the externally measured ground reaction forces (Nigg, 1986a).

Using a skin-mounted accelerometer attached to the lower leg, Valiant (1990) found peak axial accelerations of up to 2.3 g shortly after foot strike when an individual walked barefoot at a speed of 1.53 m/s and peak accelerations of up to 8.8 g when the individual ran at 3.83 m/s. Use of running shoes reduced peak accelerations associated with foot strike somewhat, to 7.9 g, when the individual ran at 3.83 m/s. The vertical shock is transmitted through the body, although there may be considerable attenuation.

Valiant (1990) measured shock transmitted to the head by use of an accelerometer mounted on a rigid bar clamped by the teeth. During running at 3.83 m/s, peak accelerations of up to 3.0 g were obtained soon after foot strike.

The repeated exposure of the body to these high loads every time the foot strikes the ground during locomotion has been implicated in the occurrence of musculoskeletal disorders, particularly overuse injuries (James, Bates, and Osternig, 1978). Dickinson et al. (1985) maintained that, although forces at foot strike can result in injury, there is an even higher probability of injury associated with the thrust phase of the gait cycle, when forces across the knee and ankle are at their maximum. Because the shoe is the principal means of attenuating the high loads to which the body is exposed during locomotion, a number of studies have been conducted to identify shoe design and material characteristics that may decrease the amplitude of the forces and thus decrease the incidence of injury.

Using a force platform, Clarke, Frederick, and Cooper (1983) tested shoes with hard and with soft midsoles on men who were trained distance runners and exhibited the force-time histories of rearfoot strikers. Two types of shoes were constructed to represent the extremes of midsole hardness. Peak g measured on an impact test device was 50% lower for the softer of the two shoe types. Clarke, Frederick, and Cooper hypothesized that the softer material would cushion or attenuate the vertical force and help prevent the body's natural shock absorbers from being overloaded. The data, collected while the subjects ran at a pace of 4.5 m/s, did not reveal a significant difference in the total vertical force impulse as a function of midsole hardness, but some significant differences in vertical force-time histories were obtained. Although the hard and the soft shoes resulted in impact peaks of similar magnitudes, the impact peak occurred significantly later with the soft shoe. Clarke, Frederick, and Cooper concluded that use of the softer material was advantageous because it resulted in the vertical force impact peak being applied to the body at a lower rate than occurred with the harder material. Furthermore, the thrust peak occurred at similar times with both shoes, but was significantly greater in the soft shoe. The authors ascribed this finding to increased heel penetration into the midsole of the softer shoe, resulting in more force produced under the ball of the foot.

Nigg, Bahlsen, Denoth, Luethi, and Stacoff (1986) reported that impact peaks may not be reduced by use of softer materials because the materials can bottom out. That is, the soft materials may reach maximum deformation before the peak forces between the ground and the foot are reached. Furthermore, Nigg et al. (1986) proposed that there is an optimal range of hardness that is dependent upon such variables as running velocity and running style. In addition, Nigg et al. (1986) and other researchers (Clarke, Frederick, and Cooper, 1983; Frederick et al., 1984) have maintained that the body adjusts its kinematics in response to the perceived hardness of the shoe.

One kinematic adjustment reported by Clarke, Frederick, and Cooper (1983) is increased knee flexion following foot strike with increases in shoe hardness. According to Miller (1990), ground reaction forces may not be sensitive to such compensatory mechanisms because ground reaction forces reflect the acceleration of the total body center of gravity. Therefore, kinematic data must be acquired and linked to the kinetic data. This was done in the present study through the recording of sagittal plane kinematics during overground walking, marching, and running. Motions at the knee, as well as at the hip, the ankle, and the metatarsals, were analyzed as a function of the type of footwear worn. Miller (1990) and others (Cavanagh, 1980; Cavanagh, Valiant, and Misevich, 1984; Milliron and Cavanagh, 1990; Nigg, 1986b) have pointed out a further limitation of ground reaction force data: These data reveal the magnitude of the forces, but not their distribution. Furthermore, the pressure distribution of primary interest is at the shoe/foot interface, not the shoe/ground interface (Cavanagh et al., 1984). To answer this need, arrays of pressure transducers have been developed that can be placed in the shoe (Cavanagh et al., 1984). This technique for acquisition of information on pressure distribution was used in the present study during overground walking, marching, and running.

In addition to the kinematic adjustment of increased knee flexion following foot strike with increases in shoe hardness (Clarke, Frederick, and Cooper, 1983; Nigg et al., 1986), another kinematic mechanism for decreasing the peak forces to which the body is exposed immediately following foot strike is pronation of the subtalar joint (Clarke, Frederick, and Hamill, 1983; Nigg et al., 1986; Nigg, Bahlsen, Luethi, and Stokes, 1987). After foot strike, there is pronation within approximately the first 50% of the contact phase, followed by supination until toe-off (Clarke, Frederick, and Hamill, 1984). Pronation of the subtalar joint consists of simultaneous calcaneal eversion, forefoot abduction, and ankle dorsiflexion. Supination involves the reverse movements of inversion, adduction, and plantar flexion (Hlavac, 1977). Although the movements of the subtalar joint act to decrease peak forces experienced by the body after foot strike, excessive pronation has been linked to injuries, particularly those of the knee and the Achilles tendon (Hlavac, 1977; James et al., 1978).

A common means of quantifying rearfoot movement is digitization of film records to measure the relative movement of the calcaneus and the lower leg during a locomotor activity. The amount of eversion of the calcaneus is considered to be a predictor of the amount of pronation that is occurring (Clarke et al., 1984). This approach was used in the present study to analyze rearfoot movement during overground walking, marching, and running in the various types of military and commercial footwear.

Cavanagh (1980) found that footwear design and construction parameters can affect the amount of maximum pronation. Clarke, Frederick, and Hamill (1983) further investigated the relationship between footwear and rearfoot movement by systematically varying the footwear parameters of midsole hardness, heel height, and heel flare.

Hardnesses of the midsoles, as measured by durometer on a Shore A scale, were 25, 35, and 45 durometers. The subjects, highly trained runners who exhibited the force-time histories of rearfoot strikers, ran on a treadmill at 3.8 m/s. Clarke, Frederick, and Hamill found that increases in heel height resulted in increases in time to maximum velocity of pronation, but had no effect on the amount of pronation. However, softer midsoles and less rearfoot flare were associated with greater maximum pronation and total rearfoot movement.

The testing done by Clarke, Frederick, and Hamill (1983) did not reveal differences in rearfoot angle at foot strike as a function of the footwear characteristics studied. Nigg et al. (1987), on the other hand, did find rearfoot angle at foot strike to be affected by midsole hardness in a study in which subjects ran over a force platform at paces of 3, 4, 5, and 6 m/s. Hardnesses of the midsoles tested by Nigg et al. were the same as those tested by Clarke, Frederick, and Hamill, 25, 35, and 45 durometers, as measured on a Shore A scale. Nigg et al. found larger rearfoot angles at foot strike with the harder midsoles and proposed that the angular differences associated with differences in midsole hardness reflected a protective mechanism, a means for controlling application of external ground reaction forces to the foot.

The fact that softer shoes have been found to offer advantages in the realm of impact cushioning (Clarke, Frederick, and Cooper, 1983) and also to be associated with excessive rearfoot motion (Clarke, Frederick, and Hamill, 1983) illustrate the conflict between two primary needs in a footwear item, protection of the body against impact loads and stability of the foot to avoid overpronation (Frederick et al., 1984; James et al., 1978). Given the additional factor of the kinematic adjustments that the body may make to mitigate the impact forces during ground contact, it is difficult to identify direct relationships between footwear characteristics and human responses during locomotor movements by relying solely on kinetic and kinematic variables. Therefore, two additional classes of dependent measures were included in this study. These were EMG data recorded from muscle groups of the leg during overground movements and physiological data recorded during treadmill movements.

Electromyography has been used as a method for studying the mechanisms controlling locomotion (Arsenault, Winter, and Marteniuk, 1986; Mann, Moran, and Dougherty; 1986; McClay, Lake, and Cavanagh, 1990). It has been found that, when a subject's velocity is constant, there is a highly repeatable pattern of muscle function for that subject, but there may be extreme differences between subjects (Arsenault et al., 1986).

Typically, in locomotion, muscle activity associated with joint motion consists of two phases. There is an active phase while the muscle experiences a lengthening, or eccentric, contracture, which produces a decelerating action on the body. This is followed by a decrease or cessation of muscle activity while the muscle experiences a shortening, or concentric, contracture, which produces a rapid movement to move the body forward (Mann et al., 1986; McClay et al., 1990). It has been proposed that levels of EMG activity may increase with the magnitudes of ground reaction forces because of the increased involvement of muscle groups in controlling movement and stabilizing body position (Williams, 1990). Electromyography was used in this study to assess the extent to which the phasic nature of muscle activity parameters may be affected by the characteristics of the footwear worn.

The physiological measures recorded in the present study during treadmill walking, marching, and running were submaximal oxygen consumption and heart rate. Both measures have been found to be affected by variations in the weight carried on the feet, although oxygen consumption appears to be the more sensitive of the two (Jones, Toner, Daniels, and Knapik, 1984; Martin, 1985). Martin (1985) recorded oxygen consumption and heart rates of men during treadmill running at 3.3 m/s with 0.25 kg or 0.50 kg of lead shot added to the lateral and the medial aspects of each shoe. A condition in which no load was added to a shoe was also included. Martin found that both oxygen consumption and heart rate increased with increases in the load. However, kinematic data did not reveal changes in the characteristics of the gait cycle as a function of load. Therefore, Martin (1985) concluded that the increase in energy cost with increasing loads on the feet was attributable to increased mechanical work required of the muscles in response to inertial changes in the lower extremity.

Jones et al. (1984) and Jones, Knapik, Daniels, and Toner (1986) analyzed submaximal oxygen consumption and heart rate of men and women during treadmill walking and running in sport shoes and Army combat boots. The walking speeds ranged from 1.11 m/s to 2.03 m/s and the running from 2.47 m/s to 3.36 m/s. Except at the slowest walking speed, both men and women showed an increment in oxygen uptake when wearing the heavier combat boot compared with the lighter-weight sport shoe. To determine whether the differences in energy cost of locomotion were attributable to weight or to design differences in the footwear, Jones et al. (1984) also tested men wearing the sport shoes with lead shot added to the lateral and medial aspects to equal the weight of the combat boots. These data indicated that weight alone accounted for a large proportion of the increased energy cost of the heavy footwear.

Non-weight related effects on oxygen consumption have also been demonstrated. Frederick (1984, 1986) reported that systematically altering the hardness of shoe materials, with shoe weight held constant, causes adjustments in oxygen consumption during running. He found that the softer shoes were associated with lower oxygen uptake. Frederick (1984, 1986) also found that the knee was flexed to a greater extent during the early contact phase with the harder shoes. He concluded that the body expends energy cushioning itself when the harder shoes are used, as compared with the softer ones, resulting in higher rates of oxygen consumption.

In addition to overground and treadmill walking, marching, and running, the men and women in the present study performed jumps onto the ground from platforms of two different heights, 0.32 m and 0.72 m. Kinetic and kinematic measures, similar to those captured during overground locomotion, were recorded during these jump/landings. The kinetic data consisted of ground reaction force-time histories as measured with a force platform on which the subjects landed. In-shoe sensors were used to measure pressure distributions between the plantar surface of the foot and the footwear. Sagittal plane and rearfoot movement kinematics were also recorded during the jump/landings, as was electromyographic activity of leg muscles.

McNitt-Gray (1991) found that peak vertical ground reaction forces in a drop from 0.72 m are approximately six times body weight, and, in a drop from 1.28 m, exceed nine times body weight. These data suggest a potential for injury during landings. However, as in overground locomotion, kinematic adjustments are made that may protect the body from injury and these vary somewhat with drop height. For example, McNitt-Grey found increases in knee and hip joint flexion, but not in minimum ankle joint dorsiflexion, with increases in height of the drop.

The subjects in the present study also performed an agility course run, with time to course completion as the dependent measure. The course was similar to one used by Robinson, Frederick, and Cooper (1986). It included 90° and 180° changes in direction, sprinting, back pedaling, stepping to the side, starting, and stopping. Robinson et al. (1986) used the course to examine the effects of the restrictive characteristics of a shoe upper on performance. The footwear used was a high-top basketball shoe. Systematic changes in ankle support were accomplished by placing sets of four stiffeners in pockets on the shoe, immediately anterior and posterior to the lateral and medial malleoli. Subjects completed the agility course without any stiffeners in the shoe and with three sets of stiffeners, each set having a different stiffness achieved through varying material modulus. The fastest course times occurred when stiffeners were not used and the slowest when the stiffeners with the highest bending moment were used. Robinson et al. (1986) concluded that the stiffeners restricted normal ranges of motion in the ankle, inhibiting the leg from obtaining positions of mechanical advantage and thus decreasing the speed of maneuvering. This study was conducted in the context of prophylactic ankle support, particularly ankle taping. However, the findings may apply as well to performance in high-top versus low-cut shoes.

As has been mentioned, the men and women participating in the present research performed the locomotor movements, jump/landings, and agility course runs in the two types of military boots and the four types of commercially available sport/work shoes. In addition to the footwear variable, a load variable was introduced into this testing. Soldiers are expected to execute physical activities while wearing backpacks and other load-carrying equipment. Therefore, responses of the human/footwear system to loads worn on the body are an important consideration in developing footwear for military use.

Much of the research done on load carriage has addressed the energy cost of carrying various load weights. For loads carried on the upper torso, it has generally been found that increases in load weight are associated with increases in energy expenditure (Gordon, Goslin, Graham, and Hoare, 1983; Pierrynowski, Winter, and Norman, 1981; Soule, Pandolf, and Goldman, 1978). In an attempt to acquire more information about load carriage than is possible from metabolic data alone, several researchers have employed biomechanical techniques in load carriage studies. Pierrynowski, Norman, and Winter (1981) filmed men walking on a treadmill without a load and with a backpack under five load weight conditions. The data were expressed in the form of mechanical work rates for the whole body and for various body segments. Pierrynowski, Norman, and Winter (1981) found that the work rates of the foot and the lower leg were lower in the unloaded condition than when loaded, but there were no differences among the five load weights in the work rates of these segments.

Kinoshita (1985) collected both kinematic and kinetic data on the effects of loads on men's walking gait. He found that ground reaction force increased in proportion to the increase in load. The kinematic data revealed greater knee flexion immediately after foot contact with the heavier load, a means of reducing the magnitude of the impact force. The foot also rotated in an antero-posterior direction around the distal ends of the metatarsal bones for a longer period of time when the heavier load was carried.

Martin and Nelson (1986) investigated the load-carrying behavior of women, as well as men, during overground walking. Sagittal plane kinematics were recorded as the subjects carried five load weights, two of which involved the carrying of loads in backpacks. Martin and Nelson found that men and women displayed different gait patterns, regardless of the load being carried. Also, in both men and women, stride length decreased and stride rate increased as load was increased. In addition, there was an increased forward inclination of the trunk when the load being carried included a backpack. These changes in walking patterns as a function of load were considerably greater for the women than for the men.

In the Army, the same footwear items are used by new recruits, many of whom are being exposed for the first time to a regular physical training regimen, and by career personnel, who have engaged in fitness training for some years. Thus, the men and women selected as participants in this study represented a range of fitness levels. Both the men and the women were divided into three fitness groups on the basis of aerobic capacity as measured by a test of maximal oxygen uptake.

Implications of Materials Testing Outcome for Human User Responses

The data from the materials testing indicated that the greatest differences between the military and the commercially available footwear were in the parameters measured on the impact test (Hamill and Bensel, 1992). Generally, the values for the combat and the jungle boots were at one extreme and the values for the Nike Air Max and the Nike cross trainer were at the other, with the values for the remaining footwear types being between the extremes. Of all the commercial items, the Red Wing work boot most often yielded values on the impact test parameters that were closest to those for the military boots (Hamill and Bensel, 1992).

With regard to peak g measured at the forefoot and the heel of the footwear on the impact test, the Nike Air Max, which was not included in the present human testing, and the Nike cross trainer, which was included, had values that were approximately half those of the military boots. The Nike Air Max and the Nike cross trainer also had the longest times to peak g. The times differed significantly from those for the military boots, which were the shortest (Hamill and Bensel, 1992). Based upon these findings for the impact test, human users would be expected to experience greater impact forces over a shorter time period when wearing the combat or the jungle boots than when using the Nike Air Max or the Nike cross trainer.

Peak pressure was another variable measured on the impact test that revealed large differences between the military and the commercial items. In both the heel and the forefoot areas, the combat and the jungle boots yielded peak pressures that were higher than those for the commercial items. The lowest values, which were obtained with the Nike Air Max and the Nike cross trainer, were approximately 50% of the values for the military boots (Hamill and Bensel, 1992). These findings suggest that human users would experience higher peak pressures at the shoe/foot interface with the military boots than with the Nike items.

With regard to the impact test results for coefficient of restitution, the military boots had among the lowest values in forefoot and the lowest values in the heel area. The highest values in both areas were associated with the Nike cross trainer (Hamill and Bensel, 1992). Thus, individuals would be expected to expend more energy during locomotion while wearing the military boots than while wearing the Nike cross trainer. The difference in energy expenditure as a function of the footwear being used would be expected to be revealed in differences in oxygen uptake or heart rate.

The mass of the footwear is another factor that may affect oxygen uptake or heart rate during performance of locomotor activities, with both physiological measures increasing in value with increases in load on the feet (Jones et al., 1984; Jones et al., 1986; Martin, 1985). The jungle boot, followed by the combat boot, was the heaviest footwear included in the study and the Nike cross trainer was the lightest. In a size 9, the masses per pair of the jungle and the combat boots exceeded that of the cross trainer by 910 g and 760 g, respectively. Martin (1985) reported a 3.3% increase in oxygen consumption with the addition of 500 g to the feet of subjects running at 3.33 m/s. Jones et al. (1984; 1986) estimated that an increase in energy cost of 0.7% to 1.0% can be expected with each 100-g increase in the mass of footwear of individuals walking or running at speeds of at least 1.56 m/s.

In addition to assessment of the impact properties of the footwear, the materials testing conducted by Bensel and Hamill (1992) included a test of flexibility of the forefoot. With the uppers in place, the Red Wing work boot was the least flexible of the items tested, followed by the combat and the jungle boots. The Nike Air Max and the Reebok Pump were the most flexible. The less flexible the footwear, the more the leg muscles may be stressed as the human user bends the foot and the shoe to propel the body forward during locomotion (Cavanagh, 1980). Thus, muscle activity levels, particularly of the gastrocnemius/soleus muscle group, would be expected to be higher when individuals are wearing the Red Wing work boot or the military boots than when they are wearing the Nike Air Max or the Reebok Pump.

Hamill and Bensel (1992) also included a measure of rearfoot stability in their materials testing of the footwear. Stability test scores are interpreted as a measure of the extent to which a shoe will resist compression, in effect remain stable, early in the ground contact phase, thereby limiting the amount or rate of subtalar joint pronation (Cavanagh, 1980). Given that excessive pronation has been linked to lower extremity injury (Hlavac, 1977; James et al., 1978), stability is a positive characteristic in a footwear item. However, pronation of the subtalar joint is a mechanism for decreasing the forces to which the body is exposed following foot strike (Clarke, Frederick, and Hamill, 1983; Nigg et al., 1986). Thus, some intermediate level of stability might be most desirable in a footwear item. Hamill and Bensel (1992) found that the combat and the jungle boots, along with the Red Wing work boot, had the highest scores for stability at both the medial and the lateral borders of the heel, whereas the Reebok Pump had the lowest. Individuals, therefore, would be expected to evidence less subtalar joint pronation at foot strike when using the Red Wing work boot or the military boots than when using the Reebok Pump.

In reviewing the previous work of Hamill and Bensel (1992), the findings from the materials testing of the footwear have served as a basis for developing projections regarding the likely outcome of human use of the footwear. However, a direct correspondence between results from materials tests and the functioning of individuals performing in the footwear cannot be assumed because the body employs compensatory mechanisms, adjusting to the physical characteristics of the footwear (Bates, 1985; Clarke, Frederick, and Cooper, 1983; Frederick et al., 1984; Nigg et al., 1986).

Furthermore, the materials tests are simulations of only some aspects of the human/footwear system, a complex biomechanical unit. On the other hand, the results from materials tests provide a perspective for viewing the functioning of the complex system.

FOOTWEAR

Each type of footwear studied is described and pictured below. The photographs include a cross-sectional view of each item. Some measurements made on the footwear are presented in Table 1. The items measured were a size 9 and had not been worn previously. The measurements included the mass of a pair of each footwear type and the height of an item from the heel or heel breast to the top. Durometer readings of the hardness of the midsole, taken on the Shore A scale, are also presented in Table 1. These data represent means obtained from readings made five times at each of several sites on the midsole of a footwear item. Measurements taken on the heel of each footwear type are presented in Table 1 as well. These measures consisted of heel flare angle, midsole height, and heel lift. Midsole height and heel lift, when summed, equal the height of the heel.

Table 1. Measurements of Footwear

Type	Mass/ Pair (kg)	Upper Height (cm)	Midsole Hardness (Shore A)	Heel Flare Angle (degrees)	Midsole Height (cm)	Heel Lift (cm)
Combat Boot	1.86	26.0	85	0	2.25	0.80
Jungle Boot	2.01	23.5	84	0	2.05	0.85
Reebok Pump	1.26	15.4	60	3	0.00	0.00
Nike Cross Trainer	1.10	12.1	55	4	0.00	0.00
Rockport Hiking Boot	1.50	13.1	55	0	1.30	1.50
Red Wing Work Boot	1.50	21.4	85	5	2.05	1.65

Combat Boot

The official nomenclature for this footwear, pictured in Figure 1, is: Boot, Combat, Mildew and Water Resistant, Direct Molded Sole. The upper, which is unlined, is fabricated of chrome tanned, grain-out, cattlehide leather, treated for mildew and water resistance. The upper has a rigid box toe, made of Surlyn®, a one-piece, combined backstay and counter pocket, and a padded collar. The heel counter is made of leatherboard. The boot closure system is a combination of eyelets and closed loops. The rubber outsole has a deep lug design, designated as the Trac Shun pattern. The outsole is direct-molded to the leather insole using a method of vulcanization. A zinc-coated steel shank extends from the middle of the heel through the arch and ends just back of the ball area. The boot has a removable Poron® insert that extends from heel to toe. The insert is made of a closed-cell, urethane foam with a fiberboard backing.

Figure 1. Three views of the combat boot.

Jungle Boot

The official nomenclature for this footwear is: Boot, Hot Weather, Type I, Black, Hot-Wet. The boot is pictured in Figure 2. The upper, which is unlined, is fabricated of leather in the foot portion and along the length of the closure system; the rest of the upper is made of a textured nylon Cordura®. Two screened eyelets are set in the leather on the medial side of the boot, in the arch area. Their purpose is to facilitate drainage of water in instances in which the boot may have been submerged. A 2.54-cm wide, nylon tape runs up the back and around the collar of the upper. There is also a 5.08-cm wide, nylon webbing stitched diagonally across the ankle. The upper has a rigid box toe of Surlyn, the same material used in the combat boot. Like the combat boot, the heel counter in the jungle boot is made of leatherboard. The removable, Poron insert is the same as that used in the combat boot. The closure system is a combination of eyelets and closed loops. The rubber outsole is patterned after heavy treads on military vehicles and is referred to as the Panama design. The outsole is direct-molded to a leather insole. The leather insole is split into two pieces and a 0.28-cm thick, stainless steel plate is inserted between the pieces and stitched around the periphery. The plate extends the entire length of the boot. As is the case with the combat boot, the jungle boot has a zinc-coated steel shank extending from the middle of the heel to just in back of the ball area.

Figure 2. Three views of the jungle boot.

Reebok Pump

This is a basketball shoe that incorporates the "pump" technology for the purpose of enhancing shoe fit. The shoe is pictured in Figure 3. The upper is constructed of "tumbled" leather. The midsole is composed of Hexalite® in conjunction with polyurethane. The outsole is made of rubber. The insert, which is glued to the midsole, is a soft foam covered with an absorbent sockliner material.

Figure 3. Three views of the Reebok Pump.

Nike Cross Trainer

This is a multipurpose, athletic training shoe. It is pictured in Figure 4. The upper is constructed of perforated synthetic mesh quarter panels and has a cut-away, exoskeleton design heel counter. The shoe also has a forefoot arch-strapping system. The midsole is a full-length, Phylon® foot-frame. The outsole has a modified waffle design with flex grooves cut in the forefoot area. The insert, a soft foam covered with a sockliner material, is contoured to provide arch support.

Figure 4. Three views of the Nike cross trainer.

Rockport Hiking Boot

This boot, which is pictured in Figure 5, has a leather upper with an internal Gore-Tex® bootie. It has a hand-sewn, moccasin construction and an internal, Hytrel® heel counter. The midsole is made of an ethyl vinyl acetate (EVA) and the outsole is a special, slip-resistant rubber compound. The insert consists of sockliner material on top of a contoured foam base.

Figure 5. Three views of the Rockport hiking boot.

Red Wing Work Boot

This is a work boot, structurally similar to the combat boot. The item is pictured in Figure 6. The Red Wing has a water-repellent, full-grain leather upper sewn to a stiff, rubber, unidensity midsole. The upper has an insulating lining throughout. In the midsole, there is a tempered steel shank extending from the heel to the arch area. The outsole is made of rubber in a Vibram® pattern and is a Goodyear welt construction. The insert is composed of a soft foam covered with a soft felt. The insert is not removable.

Figure 6. Three views of the Red Wing work boot.

METHOD

Participants

The participants in this study were drawn primarily from the Reserve Officers Training Corps (ROTC) at the University of Massachusetts-Amherst and secondarily from the remainder of the student population at the University. Participants were limited to those men and women who passed a two-phase medical screening. Candidate participants first completed a PAR-Q Physical Activity Questionnaire (British Columbia Ministry of Health, 1978), a copy of which is presented in Appendix A. A negative reply to any question was the basis for exclusion from further consideration for participation in the study. The second screening mechanism was a lower extremity evaluation conducted by a physical therapist specializing in lower extremity disorders. The examination protocol, which followed that proposed by Root, O'Brien, and Weed (1971), is outlined in Appendix A. Individuals evidencing the presence of a lower extremity disorder or a structural characteristic outside the normal range, as judged by the physical therapist, were dropped from consideration for inclusion in the study.

None of the 29 men and the 33 women who began the medical screening process were excluded from participation because of their responses on the PAR-Q Physical Activity Questionnaire. However, 14 men and 18 women were excluded because of a negative finding on the lower extremity evaluation. The remaining 15 men and 15 women served as the participants in the study.

The fitness levels of the participants were measured using a treadmill test of maximal oxygen consumption (VO_2max). Each gender was divided in to three fitness groups on the basis of the test scores. The individuals with the five highest scores comprised the high fitness group; those with the five lowest scores comprised the low fitness group; and the remaining five individuals were assigned to the medium fitness group. The physical characteristics of the groups of participants are summarized in Table 2.

Clothing and Load-Carrying Gear

The clothing worn by the participants as they were tested in each of six types of footwear included T-shirts, gym shorts, and standard Army, wool, cushion sole socks. Some of the study conditions also required that load-carrying equipment be worn. This equipment consisted of the Army's fighting and existence loads.

The basic components of the fighting load are a tactical load-bearing vest and an equipment belt. The load-bearing vest has permanently attached pockets in the chest area for ammunition and grenades. The bottom of the vest mates with the equipment belt,

Table 2. Summary of the Subjects' Physical Characteristics

Fitness Group	Age (years)	Height (m)	Mass (kg)	Body Fat (%)	VO_2max (ml/kg/min)
Men[a]					
Low (n = 5)					
M	27.6	1.80	88.2	19.9	41.3
S.D.	8.7	0.05	15.5	8.8	1.1
Medium (n = 5)					
M	25.0	1.78	70.7	15.8	51.3
S.D.	3.7	0.05	12.3	4.5	4.0
High (n = 5)					
M	24.0	1.76	74.4	13.7	59.8
S.D.	3.2	0.08	7.2	4.7	2.6
All Men (n = 15)					
M	25.5	1.78	77.8	16.5	50.8
S.D.	5.6	0.06	13.7	6.7	12.7
Women[b]					
Low (n = 5)					
M	23.8	1.55	64.5	24.3	39.8
S.D.	5.6	0.05	4.9	3.5	4.0
Medium (n = 5)					
M	22.3	1.68	62.2	26.2	48.8
S.D.	2.1	0.06	4.9	1.5	2.3
High (n = 5)					
M	21.4	1.67	66.5	22.0	58.7
S.D.	2.1	0.02	5.3	1.1	2.5
All Women (n = 15)					
M	22.5	1.63	64.4	24.2	49.1
S.D.	1.6	0.08	4.1	3.1	10.9

[a]The number of ROTC participants in each fitness group was: Low = 0; Medium = 3; and High = 5.
[b]The number of ROTC participants in each fitness group was: Low = 1; Medium = 3; and High = 4.

which is worn around the waist. The belt accommodates two canteens and canteen carriers and an entrenching tool and carrier. When outfitted with ammunition, grenades, two canteens of water, and an entrenching tool, the total mass of the fighting load is

9.1 kg (20.0 lb). A fighting load totalling 9.1 kg was used in this research, with sand bags of equivalent weights being substituted for the ammunition and the grenades.

The basic component of the existence load is a large backpack with an internal frame. The mass of this item, including the waist belt, shoulder straps, and associated hardware, is 3.4 kg (7.5 lb). Two existence loads were configured for this research. For one load, plastic bottles of water and lead weights totalling 10.2 kg (22.5 lb) were put in the pack bag to bring the total mass of the backpack, including the mass of backpack components, to 13.6 kg (30 lb). For the other existence load, the mass of the items in the pack bag was increased to 19.3 kg (42.5 lb), resulting in a total backpack mass of 22.7 kg (50 lb).

Both male and female participants were tested without any load-carrying equipment. They were also tested while wearing both the 9.1-kg fighting load and the 13.6-kg existence load. Thus, in this condition, the total mass of the load-carrying gear equalled 22.7 kg (50 lb). Male participants were tested as well while wearing the fighting load and the 22.7-kg existence load. Here, the total mass of the load-carrying gear equalled 31.8 kg (70 lb).

Apparatus

All testing was conducted in the Biomechanics Laboratory at the University of Massachusetts-Amherst. For this study, the laboratory was divided into four areas. These were: 1) a locomotor area for overground walking, marching, and running; 2) a physiological recording area for treadmill walking, marching, and running; 3) a jump/landing area; and 4) an agility course area. In the locomotor area, a rubber mat was placed on the concrete floor to delineate a runway with a 0% grade measuring 20 m in length and 1.5 m in width. The motor-driven treadmill used in the physiological recording area was a Pacer 6000 Programmable Treadmill. In the jump/landing area, there were two wooden platforms. Each had a horizontal surface 1.0 m long and 0.61 m wide. The horizontal surface of one platform was 0.32 m from the floor and the surface of the other was 0.72 m from the floor. The agility course had a 0% grade and was laid out on synthetic, gymnasium flooring in an area 13.7 m long. The route that participants were to follow was marked on the floor with tape. Figure 7 is a schematic representation of the course.

Ground reaction force data were collected during overground locomotion and jump/landings using an Advanced Mechanical Technology Incorporated (A.M.T.I.) multicomponent force platform (Model LG6-2-1). The natural frequency of the platform was 1000 Hz in the vertical direction, with a sensitivity of 1.96 mV/V/N in the vertical direction and 6.67 mV/V/N in the antero-posterior and the medio-lateral directions. The platform, which was 0.508 m long and 0.464 m wide, was installed flush with the surface of the floor. For overground locomotion, the platform was placed in the middle of the runway, permitting participants at least a 5-m approach. A diagram of the runway, showing the location of the force platform, is presented in Figure 8. For the jump/landings, the force platform was located flush with the floor immediately next to the wooden platforms.

The force platform was interfaced to a signal conditioner (A.M.T.I. Model SGA6-3) and ultimately to an IBM 486 microcomputer via a 12-bit, analog-to-digital (A/D) converter (Data Translation Model DT2801). Force platform output was sampled at 1000 Hz.

During overground walking, marching, and running, the participant's speed was monitored by two photoelectric cells (Safe House Infrared Photorelay Beam alarms) interfaced to a digital clock accurate to 0.001 s. The photoelectric cells were placed 5 m apart as indicated in Figure 8.

Pressure measurements at the shoe/foot interface were made during overground locomotion and the jump/landings using a thin filament substrate in which 960 pressure sensors were embedded. The sensors were activated by vertical stresses and were placed in the right shoe. The in-shoe pressure measurement device, which is produced by Tekscan, Inc., resembled a commercial shoe insert and extended the full length of the shoe. The pressure sensors were interfaced to a microcomputer via an A/D converter. Sensor outputs were sampled at 100 Hz. The pressure measurement device was calibrated to the participant's body weight.

Two high-speed video cameras (NAC Model MOS V-14), which ran at 200 Hz, two video recorders (NAC Model VTR V-32), and two control boxes (NAC Model V-33) were used to acquire kinematic data during overground locomotion and the jump/landings. One camera was placed to the right side of the participant and the other to the rear. The locations of the cameras are shown in Figure 8. The same camera placements were used for the jump/landings.

The video-taped images were digitized in real time using a Motion Analysis video processor (Model VP-110) interfaced to a Sun Microsystems minicomputer. The data were filtered using a 4th order Butterworth low-pass filter with a selective cut-off frequency for each x and y coordinate determined by the procedure of Jackson (1979).

The EMG data acquired during overground walking, marching, and running and during the jump/landings were collected from four muscle groups using pre-amplified, silver-silver chloride surface electrodes (Therapeutics Unlimited) and a multichannel electromyographic processor (Therapeutics Unlimited Model 544). The amplifier used had the following characteristics: input impedance of greater than 25 megohms at DC;

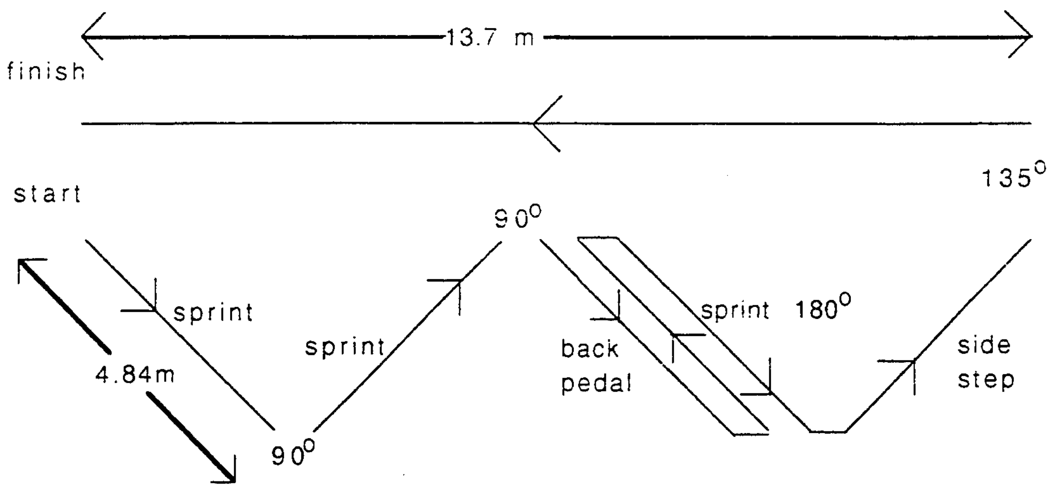

Figure 7. Schematic representation of the agility course.

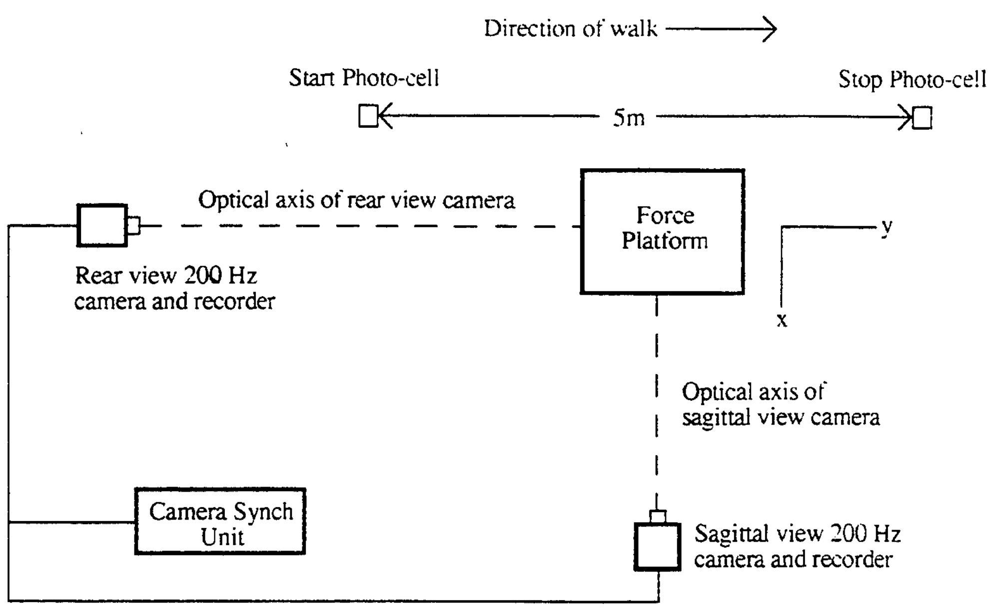

Figure 8. Diagram of the runway showing locations of apparatus.

common mode rejection ratio of 87 dB at 60 Hz; gain linearity of $\pm 0.5\%$; frequency response of 20 Hz to 4000 KHz; a gain of 1000 to 100,000; and noise of 1.5 microvolts RMS.

The raw EMG signals from each muscle group were sampled at 1000 Hz simultaneously with the force platform output using the same A/D converter and microcomputer. The EMG signals were full-wave rectified and digitally filtered using a low-pass filter with a cut-off frequency of 20 Hz to create a linear envelope.

During overground locomotion and the jump/landings, capture of the in-shoe pressure, the kinematic, the EMG, and the ground reaction force data were synchronized using an LED switch that was triggered when the vertical force component output of the force platform reached a magnitude of 5 N.

Metabolic, ventilatory, and heart rate variables were measured while participants walked, marched, and ran on the treadmill. Heart rate was recorded using a Vantage Performance Monitor telemetry device from Polar Electro, Inc. Twenty-second samples of oxygen uptake (VO_2) and carbon dioxide production (VCO_2) were obtained using a Gould 9004 metabolic cart. Inspired ventilation was assessed using a dry gas meter and the analog signal was converted to a digital output via an A/D converter. Software was then used to convert the inspired ventilation to expired ventilation using the Haldane transformation. Expired air was directed into a 5-L mixing chamber and was continuously sampled using oxygen and carbon dioxide analyzers interfaced to the A/D converter. The spirometer was calibrated at the beginning of each testing day with a 3-L syringe. The gas analyzers were calibrated before each test session. Known gas concentrations of 5.04% CO_2 and 100% O_2, along with atmospheric air, were used to calibrate the gas analyzers.

Procedure

Preliminary Session

Each participant completed one preliminary and eight experimental sessions. The first, or preliminary, session included executing the volunteer agreement, measuring body dimensions, determining body density and lean body mass through hydrostatic weighing, performing a protocol to determine maximal oxygen uptake, and fitting of the footwear. To determine the sizes in each footwear type to be worn during the experimental sessions, a participant first tried on shoes that were within a half-size of the size that the participant reported usually wearing. Additional sizes were tried as necessary until the participant reported a good fit. All fitting was done while the participant was wearing the standard Army socks.

For the underwater weighing, the participant sat on a chair suspended from a scale (9-kg Chatillon autopsy scale). The chair initially hung above a water tank and was gradually lowered, submerging the participant. The participants were asked to exhale to their full capacity as their heads were lowered under the water and to hold their breath for 5 s to 10 s while underwater body weight was measured. This procedure was repeated 10 times for a participant and the mean of the 10 trials was used in the following equation (McCardle, Katch, and Katch, 1991) to calculate the participant's body density.

$$\text{Body density} = M_a \times D_W / (M_a - M_W - RV \times D_W)$$

where M_a = mass of body in air
M_W = mass of body in water
D_W = density of water
RV = residual lung volume

The body density value was then inserted into the Siri (1961) equation to determine percentage of body fat.

$$\%\ \text{body fat} = (495 / \text{body density}) - 450$$

After the underwater weighing, the participants underwent the test of maximal oxygen uptake to determine assignments to the fitness groups. For this test, a comfortable jogging speed was first determined for a participant. The participant ran at this constant speed on the motor-driven treadmill. Treadmill grade was increased by 2.5% every 2 min from an initial 0% until the participant reached the point of volitional exhaustion.

During the treadmill test, heart rate was monitored continually using the heart rate monitor, which calculated and stored the 60-s averages. The participant breathed atmospheric oxygen through a two-way, non-rebreathing valve (Hans Rudolph, Inc. 2700 series, large 2-way NRBV). The expiratory side of the valve was connected to the volume displacement 10-L spirometer of the metabolic cart. A thermistor temperature probe located within the spirometer cylinder converted the measured volume to standardized values (STBD). Flow information was obtained by electronic differentiation of the volume signal. The spirometer served as the mixing chamber for expired gases. A sample of gas was drawn through a desiccant chamber from the spirometer every 30 s. After passing through the desiccant chamber, the gas sample was drawn in to the analyzers.

The criteria used to determine VO_2max included a respiratory exchange ratio in excess of 1.1, a heart rate within 15 beats of the age-predicted maximal heart rate, that is, 220 - age in years (McCardle et al., 1991), and a leveling off in oxygen consumption (VO_2) despite an increase in work.

Experimental Sessions

A participant performed a different activity at each of the eight experimental sessions that followed the preliminary session. Overground walking, marching, and running each entailed one session, as did treadmill walking, marching, and running. Jump/landings from the two heights comprised the activity at another session and the agility run was done at yet another session.

A participant's testing schedule was structured such that the overground walking session was always followed, on the next day, by the treadmill walking session. There was then a break of at least five days in the testing of that participant. This same approach was taken in the scheduling of the marching and the running activities: The activity was first performed overground, followed, on the next day, by performance of that activity on the treadmill, followed by a minimum of five-days break. The jump/landing and the agility run sessions were also followed by a break of at least five days in the participant's testing schedule. To determine the order of presentation of the walking, marching, running, jump/landing, and agility run activities, five unique sequences were established; three men and three women were assigned each order.

At each of the experimental sessions, a participant was tested in all six types of footwear included in this study. During an experimental session, the women used each type of footwear under two load conditions: without load-carrying gear and with fighting and existence load-carrying gear totalling 22.7 kg. The men used each type of footwear under these two load conditions plus a third condition consisting of a fighting and an existence load totalling 31.8 kg. Thus, a woman was exposed to 12 footwear and load combinations at a session and a man was exposed to 18.

To determine the order of presentation of the footwear conditions, six unique sequences were established. Two men and two women were randomly assigned each sequence. The remaining three men and three women were also assigned one of the sequences, which was randomly selected from among the six. The load conditions were balanced across each gender under each footwear condition. A participant had the same order of footwear and load conditions throughout all testing. That is, the same order for overground walking as for overground marching, treadmill running, etc.

Overground Walking, Marching, and Running

Preparation for testing at a session during which a participant was to carry out overground walking, marching, or running included placing a pressure measurement device in the right member of the pair of shoes that the participant was to test first. Also, seven retroreflective markers were affixed on the right lateral surface of the body. These markers were used subsequently to generate coordinate data during digitization of the videotaped images taken in the sagittal plane. The anatomical locations of the markers, which followed the protocol of Winter (1990), are pictured in Appendix B. All anatomical locations were identified via palpation. The locations of the markers were:

Iliocristale, highest point on the iliac crest of the pelvis
Greater trochanter of the femur
Lateral femoral epicondyle
Lateral malleolus
Heel, about 2 cm above the ground
Protrusion of the 5th metatarsal-phalangeal joint
Most anterior projection of the foot as viewed in the sagittal plane.

Retroreflective markers were also affixed to the posterior aspect of the lower leg and the foot for use in the kinematic analysis of rearfoot movement. The protocol of Clarke, Frederick, and Hlavac (1983) was followed. Marker placement was standardized by having the participants stand with their feet in a jig. The jig kept the heels 5 cm apart and the forefeet abducted at a 7° angle. Two markers were placed 20 cm apart on the right lower leg such that a line joining them was parallel to the long axis of the lower leg. The distal marker was placed in the midline of the Achilles tendon between the medial and the lateral malleoli, and the proximal marker was located below the belly of the gastrocnemius on a line joining the distal marker with the bisection of the leg at the level of the popliteal fossa. The markers were affixed to the skin or the footwear, depending upon the height of the footwear. Two markers were also placed on a line that approximated the bisection of the posterior aspect of the right calcaneus, as well as could be estimated in the presence of the footwear. This line was drawn in relation to the calcaneus, not to the vertical. The locations of the markers are illustrated in Appendix B.

In addition to the retroreflective markers, surface electrodes for EMG recording were affixed to the right thigh and lower leg prior to overground walking, marching, or running. The electrodes were placed over the medial hamstring, the rectus femoris, the anterior tibialis, and the gastrocnemius/soleus muscle groups. To standardize placement of the electrodes from session to session, lines indicating electrode locations were drawn on the participant's skin with an indelible marker.

The speeds selected for walking, marching, and running were 1.15 m/s, 1.50 m/s, and 3.40 m/s, respectively. The walking and the running speeds were based upon previous studies (Hamill, Bates, and Knutzen, 1984). The marching speed was based on a 30-in. step and a rate of 120 steps/min. Before testing began for a given movement, participants practiced maintaining the proper speed while traversing the runway and contacting the force platform without altering their gait. The participants were to contact the force platform with the right foot.

During practice in walking and running and throughout the trials that followed, participants used a self-selected stride rate and were coached by the experimenter in maintaining the criterion speed. For marching, a metronome was used to pace the participants.

A participant performed 10 acceptable trials in a given footwear-load combination before being tested in the next combination. An acceptable trial was one in which the participant's speed was within $\pm 5\%$ of the prescribed speed for the locomotor movement and in which the right foot contacted the force platform. It has been found that 10 trials are adequate to establish stable means of ground reaction force parameters (Hamill and McNiven, 1991). Within a block of trials for a particular footwear-load combination, there was a break of at least 1.5 min between trials; longer breaks were taken at the participant's discretion. Between trial blocks, there was a break of at least 5 min and, again, longer breaks were taken at the participant's discretion.

Before each 10-trial block, the participant was videotaped while standing in a static posture. These frames were used for calibration purposes in subsequent treatment of the sagittal plane and rearfoot movement data. In the sagittal plane, the calibration frames defined 0° of flexion or extension. In the rearfoot view, the rearfoot angle in the calibration frames was subtracted from the dynamic angle.

Treadmill Walking, Marching, and Running

The treadmill grade was kept at 0% throughout all walking, marching, and running trials. For a given locomotor movement, the speed of the motor-driven treadmill was set to correspond to the overground speed for the movement. That is, treadmill walking, marching, and running were done at 1.15 m/s, 1.50 m/s, and 3.40 m/s, respectively. Treadmill speed was checked regularly with a tachometer.

A participant's trial consisted of a 7-min bout at the prescribed speed. A 5-min to 7-min period of locomotion has been found to be sufficient to attain a steady-state metabolic response (Stainsby and Barclay, 1970). A participant had one trial under each footwear-load combination. During a trial, heart rate and respiratory gas exchange were measured continuously. There was a break between trials of at least 5 min and the break was extended at the participant's discretion.

Jump/Landings

Preparations for jump/landing testing were similar to those carried out prior to overground locomotor testing. That is, a pressure measurement device was placed in the right member of a pair of footwear and retroreflective markers and EMG electrodes were affixed to the participant's body. The markers and the electrodes were placed in the same locations used during the overground movements. A participant executed practice jumps from each of the two platform heights prior to testing.

During testing, a participant completed five jumps from one height under each footwear and load combination before executing five jumps from the other height under each combination. Eight participants of each gender jumped from the 0.32-m platform first; the remaining seven participants were exposed to the two heights in the opposite order.

The jump/landing testing followed the protocol of McNitt-Gray (1991). A participant initiated a jump by stepping out from the platform with the left leg straight and the right leg extended slightly forward. The landing was performed by contacting the force platform with both feet simultaneously, without any extra steps or hops. The impact velocities for jumps from the low and the high platform heights were 2.50 m/s and 3.75 m/s, respectively. Within a block of trials at a particular height, there was a break of at least 1.5 min between trials; longer breaks were taken at the participant's discretion. Between trial blocks, there was a break of at least 5 min and longer breaks were taken at the participant's discretion.

Agility Course Run

The protocol used for the agility course runs followed that employed by Robinson et al. (1986). Prior to testing, the participant was instructed regarding the course and was walked through it. The participant then completed the course slowly several times. Preliminary, timed trials were then conducted until the participant completed two, successive runs through the course that differed in duration by not more than 0.10 s.

During testing, a trial consisted of one run through the course; the time to complete the run was recorded to the nearest 0.01 s. A participant had three trials in a given footwear-load combination before being tested on the next combination. Within a block of three trials, the participant determined the duration of the breaks between trials. Between trial blocks, there was a break of at least 5 min, and longer breaks were taken at the participant's discretion.

Dependent Measures

The data acquired in this study varied with the physical activity being performed by the participants and with the measurement techniques employed during the activity. The dependent variables associated with each activity and the raw data subsequently subjected to statistical analysis are described here. Additional explanatory information on the dependent measures is presented in Appendix B.

Overground Walking, Marching, and Running

The measurements taken for overground walking, marching, and running were identical, and the data from the three movements were treated in the same manner. The movements were analyzed separately; statistical analyses were not done to compare them with regard to the dependent measurements.

Six vertical (Fz), five antero-posterior (Fy), and two medio-lateral (Fx) force and temporal variables were generated from the force platform output (Bates, Osternig, Sawhill, and Hamill, 1983). These ground reaction force-time variables describe the foot contact, or support, phase of the locomotor activity, that period that began at foot strike with the force platform and continued through toe-off. The ground reaction forces were normalized by dividing by the participant's body mass. Temporal parameters were expressed as percentages relative to the total support period.

The specific parameters used to describe the three components of the ground reaction force-time curves are listed below. Graphic representations of the parameters are presented in Appendix B.

<u>Vertical Force Component</u>

Fz1 -- first maximum force, the amplitude of the first force peak (N/kg of body mass)
Fz2 -- relative time to first maximum force (%)
Fz3 -- second maximum force, the amplitude of the second force peak (N/kg of body mass)
Fz4 -- relative time to second maximum force (%)
Fz5 -- average vertical force, calculated over readings taken at the rate of 1000 Hz (N/kg of body mass)
Fz6 -- total vertical impulse, calculated as the area under the force-time curve ($N \cdot s$/kg of body mass)

<u>Antero-posterior Force Component</u>

Fy1 -- maximum braking force, the amplitude of the largest negative force peak (N/kg of body mass)
Fy2 -- relative time to maximum braking force (%)

Fy3 -- relative time to transition force (%)
Fy4 -- maximum propelling force, the amplitude of the largest positive force peak (N/kg of body mass)
Fy5 -- relative time to maximum propelling force (%)

Medio-lateral Force Component

Fx1 -- force excursions 0-30% of contact period (N/kg of body mass)
Fx2 -- force excursions 0-100% of contact period (N/kg of body mass)

For each ground reaction force-time parameter, a mean was obtained over the 10 trials that a participant carried out under a single footwear-load combination. The means were then used as the raw data in the statistical analyses.

For the measurement of in-shoe pressure, the data recorded during foot contact with the force platform were selected for further analysis. Three parameters were used to describe pressure at the shoe/foot interface. These are listed here and illustrated in Appendix B.

In-shoe Pressure

P1 -- peak heel pressure (kPa)
P2 -- peak forefoot pressure (kPa)
P3 -- total movement distance of center of pressure (cm)

As was done with the ground reaction force parameters, a mean was obtained for each parameter over the 10 trials that a participant carried out under a single footwear-load combination. The means were the raw data used in the statistical analyses.

For the sagittal plane kinematics, parameters were calculated that described the action at the hip, the knee, the ankle, and the metatarsal joints during one stride. The stride selected for analysis was right foot strike of the force platform through the next right foot strike. Temporal parameters were expressed relative to initial contact of the right foot with the force platform. The conventions followed in calculating the joint angles are illustrated in Appendix B. The parameters are as follows:

Hip

H1 -- maximum flexion (degrees)
H2 -- maximum extension (degrees)
H3 -- maximum flexion velocity (degrees/s)
H4 -- time to maximum flexion velocity (ms)
H5 -- maximum extension velocity (degrees/s)
H6 -- time to maximum extension velocity (ms)

<u>Knee</u>

K1 -- maximum flexion during support (degrees)
K2 -- maximum extension (degrees)
K3 -- maximum flexion velocity (degrees/s)
K4 -- time to maximum flexion velocity (ms)
K5 -- maximum extension velocity (degrees/s)
K6 -- time to maximum extension velocity (ms)

<u>Ankle</u>

A1 -- maximum plantarflexion (degrees)
A2 -- maximum dorsiflexion (degrees)
A3 -- maximum plantarflexion velocity (degrees/s)
A4 -- time to maximum plantarflexion velocity (ms)
A5 -- maximum dorsiflexion velocity (degrees/s)
A6 -- time to maximum dorsiflexion velocity (ms)

<u>Metatarsal</u>

Mt1 -- maximum flexion (degrees)
Mt2 -- time to maximum flexion (ms)
Mt3 -- maximum flexion velocity (degrees/s)
Mt4 -- time to maximum flexion velocity (ms)

Again, for purposes of analysis, a mean was obtained for each parameter over the 10 trials that a participant carried out under a single footwear-load combination. The means were the raw data used in the statistical analyses.

Five parameters, which were based upon movement of the calcaneus relative to the lower leg, were used to describe rearfoot movement during one support phase. The data recorded during foot contact with the force platform were analyzed. Temporal parameters were expressed relative to initial contact of the right foot with the force platform. The conventions followed in calculating the parameters are illustrated in Appendix B. The parameters are as follows:

<u>Rearfoot Movement</u>

Rf1 -- rearfoot angle at foot strike (degrees)
Rf2 -- maximum rearfoot angle, the largest angle during the foot contact phase (degrees)
Rf3 -- time to maximum rearfoot angle (ms)
Rf4 -- total rearfoot motion, calculated as the sum of the absolute values of Rf1 and Rf2 (degrees)
Rf5 -- maximum rearfoot velocity (degrees/s)

A mean was obtained for each parameter over the 10 trials that a participant carried out under a single footwear-load combination. The means were the raw data used in the statistical analyses.

The EMG data analyzed from each of the four muscle groups were the data captured during the stride that began with right foot strike of the force platform. To derive temporal parameters for analysis, the time of foot strike was set equal to 0 ms; occurrence of muscle activity over the stride cycle was expressed relative to foot strike. The area under the linear envelope of the EMG-time curve for each muscle group was also calculated to assess the amplitude characteristics of the signal. The EMG parameters analyzed are as follows:

EMG

EMG1 -- time to onset of muscle activity, relative to foot strike (ms)
EMG2 -- time to end of muscle activity, relative to foot strike (ms)
EMG3 -- area (V•s)

For each of the muscle groups, a mean was obtained for a parameter over the 10 trials that a participant carried out under a footwear-load combination. The means were subsequently used in the statistical analyses.

Treadmill Walking, Marching, and Running

As was the case for the overground activities, the measurements taken for treadmill walking, marching, and running were identical, and the data from the three movements were treated in the same manner. The movements were analyzed separately; statistical analyses were not done to compare them with regard to the dependent measures.

Three physiological variables were used to describe treadmill locomotion. They included oxygen uptake rate and respiratory exchange ratio (RER). The latter is the ratio of carbon dioxide produced to oxygen consumed. These metabolic parameters were derived from the final four, 20-s samples taken during a participant's 7-min bout of locomotion under a particular footwear-load combination. A mean for each parameter was obtained over the four samples and was used in subsequent statistical analyses. Heart rate, the third physiological variable, was treated in a similar manner. A mean was calculated from the rate recorded during each of the final four, 30-s periods of locomotion under a particular footwear-load combination. The mean was then used in subsequent statistical analyses. The three physiological variables are as follows:

Physiological Variables
M1 -- oxygen uptake (ml/kg of body mass/min)
M2 -- RER (dimensionless)
M3 -- heart rate (beats/min)

Jump/Landings

The measurements taken in the five trials carried out at each platform height were identical. Also, the data acquired at the two heights were treated in the same manner. The two heights were analyzed separately; statistical analyses were not done to compare them with regard to the dependent parameters.

Six vertical force (LFz) and temporal variables were generated from the force platform output. These ground reaction force-time variables describe the landing phase of the jump, that period extending from touchdown (initial contact of the feet with the force platform) through the time at which the participant's vertical force curve became constant at the magnitude of body weight. The majority of the six variables address the impact peak force, or the peak magnitude of the vertical reaction force experienced during landing. One of the variables, impact ratio, was a derived measure obtained by dividing the vertical impulse experienced prior to the time of impact peak force by the vertical impulse experienced over the entire landing phase. The ground reaction forces associated with the jump/landings were not normalized to the participant's body mass, as was done with the forces associated with overground locomotion. In addition, the jump/landing temporal parameters were not expressed as percentages, but as actual time elapsed from foot contact.

The specific parameters used to describe the vertical force-time component of the jump/landings are listed below. Graphic representations of the parameters are presented in Appendix B.

Vertical Force Component
LFz1 -- first maximum force, the impact peak force (N)
LFz2 -- time to first maximum force (ms)
LFz3 -- slope of first maximum force (N/s)
LFz4 -- impact ratio (%)
LFz5 -- second maximum force (N)
LFz6 -- time to second maximum force (ms)

For each vertical ground reaction force-time parameter, a mean was obtained over the five trials that a participant carried out at a single height under a single footwear-load combination. The means were then used as the raw data in the statistical analyses.

The in-shoe pressure parameters for the jump/landings were the same as those used for the overground locomotor activities. The data recorded during the landing phase were selected for further analysis. The three parameters were used to describe pressure at the shoe/foot interface are listed here and illustrated in Appendix B.

<u>In-shoe Pressure</u>

LP1 -- peak heel pressure (kPa)
LP2 -- peak forefoot pressure (kPa)
LP3 -- total movement distance of center of pressure (cm)

As was done with the ground reaction force-time parameters, a mean was obtained for each parameter over the five trials that a participant carried out at a single height under a single footwear-load combination. The means were the raw data used in the statistical analyses.

For the sagittal plane kinematics of the jump/landings, parameters were calculated that described the action at the hip, the knee, the ankle, and the metatarsal joints during a jump/landing. The data analyzed were those recorded during the landing phase. Temporal parameters were expressed relative to contact of the right foot with the force platform. The conventions followed in calculating the joint angles are illustrated in Appendix B. The parameters are as follows:

<u>Hip</u>

LH1 -- maximum flexion (degrees)
LH2 -- time to maximum flexion (ms)
LH3 -- maximum flexion velocity (degrees/s)
LH4 -- time to maximum flexion velocity (ms)

<u>Knee</u>

LK1 -- maximum flexion (degrees)
LK2 -- time to maximum flexion (ms)
LK3 -- maximum flexion velocity (degrees/s)
LK4 -- time to maximum flexion velocity (ms)

<u>Ankle</u>

LA1 -- maximum dorsiflexion (degrees)
LA2 -- time to maximum dorsiflexion (ms)
LA3 -- maximum dorsiflexion velocity (degrees/s)
LA4 -- time to maximum dorsiflexion velocity (ms)

<u>Metatarsal</u>

LMt1 -- maximum flexion (degrees)
LMt2 -- time to maximum flexion (ms)
LMt3 -- maximum flexion velocity (degrees/s)
LMt4 -- time to maximum flexion velocity (ms)

Again, for purposes of analysis, a mean was obtained for each parameter over the five trials that a participant carried out at each of the two heights under a single footwear-load combination. The means were the raw data used in the statistical analyses.

Five parameters, based upon relative movement of the calcaneus and the lower leg, were used to describe rearfoot movement during the jump/landings. Again, the data analyzed were those acquired during the landing phase and temporal parameters were expressed relative to contact of the right foot with the force platform. The conventions followed in calculating the parameters are illustrated in Appendix B. The parameters are as follows:

<u>Rearfoot Movement</u>

LRf1 -- rearfoot angle at touchdown (degrees)
LRf2 -- maximum rearfoot angle (degrees)
LRf3 -- time to maximum rearfoot angle (ms)
LRf4 -- total rearfoot motion (degrees)
LRf5 -- maximum rearfoot velocity (degrees/s)

A mean was obtained for each parameter over the five trials that a participant carried out at a single height under a single footwear-load combination. The means were the raw data used in the statistical analyses.

As was done for overground locomotion, three EMG parameters were established for the jump/landings. The data analyzed from each of the four muscle groups consisted of those acquired during the landing phase. To derive temporal parameters for analysis, the time of touchdown was set equal to 0 ms; occurrence of muscle activity over the cycle was expressed relative to touchdown. The area under the linear envelope curve for each muscle group was also calculated to assess the amplitude characteristics of the signal. The EMG parameters analyzed are as follows:

<u>EMG</u>

LEMG1 -- time to onset of muscle activity, relative to touchdown (ms)
LEMG2 -- time to end of muscle activity, relative to touchdown (ms)
LEMG3 -- area ($V \cdot s$)

For each of the muscle groups, a mean was obtained for a parameter over the five trials that a participant carried out at each of the two heights under a footwear-load combination. The means were subsequently used in the statistical analyses.

Agility Course Run

The agility course run involved analysis of only one parameter, time to course completion. A mean was obtained over the three trials that a participant carried out under a footwear-load combination. The means were subsequently used in the statistical analyses.

Statistical Analyses

An analysis of variance (ANOVA) was used to analyze each of the dependent measures. The data of the men and the women were treated separately. For both genders, the design of the analysis was a hierarchical one, with one between-subjects and two within-subjects factors. The form of the analysis of the men's data was: Footwear (combat boot, jungle boot, Reebok Pump, Nike cross trainer, Rockport hiking boot, Red Wing work boot) by Load (0 lb, 50 lb, 70 lb) within Fitness Group (low, medium, high). There were five men in each fitness group. The male data were complete. That is, there were no missing data points. The structure of the ANOVAs applied to the male data, including the degrees of freedom, is presented in Table 3.

The form of the analysis of the female data was the same as that of the men's, with the exception of the levels of the load factor. The women were tested under only two levels of the load variable, 0 lb and 50 lb. There were five women in each fitness group. As was the case with the men, there were no missing data points in the women's data. The structure of the ANOVAs applied to the female data, along with the degrees of freedom, is presented in Table 3.

As was detailed previously, several categories of measurements were recorded to describe each of the physical activities performed by the participants, with the exception of the agility course run, in which only time was recorded. Each measurement category included at least two dependent measures. For example, five parameters were recorded to describe rearfoot movement during walking, six to describe the vertical force component of this activity, etc. Because of the large number of dependent measures for a given physical activity, and thus the likelihood of Type I errors, a conservative approach, employing the Bonferroni inequality, was taken to testing for significance of the ANOVAs (Stevens, 1986). This was done by setting the significance level for the ANOVAs performed within a measurement category at $p < .05$ and dividing this by the

Table 3. Structure of ANOVAs

	df		
Source of Variance	Men	Women	*F* ratio
Between Ss			
Fitness (F)	2	2	MS_F / $MS_{Ss/F}$
Ss / F	12	12	—
Within Ss			
Footwear (W)	5	5	MS_W / $MS_{SsxW/F}$
F x W	10	10	MS_{FxW} / $MS_{SsxW/F}$
Ss x W / F	60	60	—
Load (L)	2	1	MS_L / $MS_{SsxL/F}$
F x L	4	2	MS_{FxL} / $MS_{SsxL/F}$
Ss x L / F	24	12	—
W x L	10	5	MS_{WxL} / $MS_{SsxWxL/F}$
F x W x L	20	10	MS_{FxWxL} / $MS_{SsxWxL/F}$
Ss x W x L / F	120	60	—

number of dependent measures associated with that category. Thus, the significance level for the *F* ratios in the five ANOVAs performed on the data for rearfoot movement during walking was $p < .01$.

In those instances in which a main effect was found to be significant, Tukey's honestly significant difference procedure (*HSD*) was applied as a post-hoc test, with the significance level again set at $p < .05$.

RESULTS AND DISCUSSION

The results of the statistical analyses done on the dependent measures for walking, marching, running, jump/landings, and the agility course are presented separately in the sections that follow. The activities of walking, marching, and running were performed overground in order to capture kinetic, kinematic, and electromyographic data and on a treadmill in order to capture metabolic and heart rate data. For the jump/landings from 0.32 m and from 0.72 m, kinetic, kinematic, and electromyographic data were recorded, but metabolic and heart rate data were not acquired. On the agility course run, time to completion was the only measure recorded.

The values of all *F* ratios for each ANOVA are contained in appendix tables. The appendix tables also include the means at each level of the fitness, the footwear, and the load variables. In addition, the outcomes of the *HSD* procedure applied to the significant main effects are indicated in the tables. The large volume of data collected in this study prohibits presentation of the means associated with all interactions for all dependent measures. However, given that footwear is the focus of this research and that the carrying of loads is basic to the situation of foot soldiers, the means describing the interaction between footwear and load are presented in the appendix tables for all dependent measures.

Because of the large number of parameters captured during the walking, marching, running, and jump/landing activities, the results below for each of these activities begin with summary text and tables. The summary is followed by more detailed information on the findings from the analyses of the various dependent measures and then by a discussion of the findings. Again because of the extensive amount of data collected, as well as the fact that the focus of this work is on the footwear studied, the presentation of the results addresses only those sources of variance involving the footwear variable. Furthermore, in the discussion, the emphasis is on footwear, specifically the extent to which the findings for the combat and the jungle boots differ from those for the commercial footwear.

Overground and Treadmill Walking (1.15 m/s)

Results

Summary

Those interactions that were significant in the analyses of the parameters measured during overground and treadmill walking are noted in Table 4 for both the men and the women. As indicated in the table, none of the analyses revealed a significant second-order interaction. However, analyses of both the male and the female data did reveal significant interactions between fitness and footwear. For the men, the significant

Table 4. Significance of Main Effects and Summary of Significant Interactions in the Analyses of Overground and Treadmill Walking Parameters

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Vertical Ground Reaction Force Component			
Fz1	---[b]	---[b]	.001	.001	.001[b]	.001[b]
Fz2	---	---	---	.005	---	---
Fz3	---[a,b]	---[b]	.001[a]	.001	.001[b]	.001[b]
Fz4	---	---[b]	---	---	---	.001[b]
Fz5	---[b]	---[b]	---	---	.001[b]	.001[b]
Fz6	---[b]	---[b]	.001	.001	.001[b]	.001[b]
			Antero-posterior Ground Reaction Force Component			
Fy1	---[b]	---[a,b]	.001	---[a]	.001[b]	.001[b]
Fy2	---[a,b]	---	.001[a]	.001	---[b]	---
Fy3	---	---	---	---	---	---
Fy4	---[b]	---[b]	---	---	.001[b]	.001[b]
Fy5	---	---	.005	.001	---	---

Table 4. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
	Medio-lateral Ground Reaction Force Component					
Fx1	---	---	---	---	---	---
Fx2	---[b]	---[a,b]	---	---[a]	---[b]	.001[b]
	In-shoe Pressure					
P1	---	---	---	---	---	---
P2	---	---	---	---	---	---
P3	---	---	---	---	---	---
	Sagittal Plane Kinematics - Hip Angle					
H1	---[b]	---[b]	---	---	.001[b]	.001[b]
H2	---[b]	---[b]	---[c]	---	.001[b,c]	.001[b]
H3	---[b]	---	---	---	.001[b]	.001
H4	---[b]	---[b]	.001	.005	.001[b]	.001[b]
H5	---[b]	---	---	---	.001[b]	---
H6	---[b]	---[b]	.001	---	.001[b]	.001[b]

Table 4. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Knee Angle			
K1	---	---	.001	.005	---	---
K2	---	---[b]	---	---	.001	.001[b]
K3	---	---[b]	.001	.001	.001	.001[b]
K4	---	---[b]	.001	---	.001	.001[b]
K5	---	---	---	.001	---	---
K6	---	---	.001	---	.001	.001
			Sagittal Plane Kinematics - Ankle Angle			
A1	---[b]	---[a,b]	.001	.001[a]	.001[b]	.005[b]
A2	---[b]	---	.001	.001	.001[b]	.001
A3	---[a,b]	---	.001[a]	.001	.001[b]	---
A4	---[b]	---	---	---	.001[b]	.001
A5	---	---	.001	---	.005	---
A6	---	---	---	.001	---	---

Table 4. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Metatarsal Angle			
Mt1	---[a,b]	---[a,b]	.001[a]	.001[a]	.001[b]	.001[b]
Mt2	---[b]	---[b]	.001	---	.001[b]	.001[b]
Mt3	---[a,b]	---[b]	.001[a,c]	.001	.001[b,c]	.005[b]
Mt4	---[b]	---	.001	---	.001[b]	.001
			Rearfoot Movement			
Rf1	---	---	.005	---	---	---
Rf2	---	---	---	.001	---	---
Rf3	---	---	.005	---	.01	---
Rf4	---	---	---	.01	---	---
Rf5	---	---	---	.001	---	---
			EMG - Medial Hamstring			
EMG1	---	---	.001	---	---	---
EMG2	---	---	---	---	---	---
EMG3	---	---	---	---	---	---

Table 4. Continued

Parameter	Source of Variance: Fitness		Footwear		Load	
	Men	Women	Men	Women	Men	Women
EMG - Rectus Femoris						
EMG1	---	---	---	---	---	---
EMG2	---[b]	---[b]	---	.01	.001[b]	---[b]
EMG3	---[b]	---	---	---	.001[b]	---
EMG - Anterior Tibialis						
EMG1	---	---	---	---	---	---
EMG2	---	---	.001	---	---	---
EMG3	---	---	---	---	---	---
EMG - Gastrocnemius/Soleus						
EMG1	---	---	---	---	---	---
EMG2	---	---	---	---	---	---
EMG3	---	---	---	---	.005	---

Table 4. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Physiological Measures			
M1	---	---	---	.005	.005	---
M2	---	---	---	---	---	---
M3	---	---	---	---	---	---

Note. Dashes indicate a nonsignificant main effect.

[a]Significant Fitness x Footwear interaction. [b]Significant Fitness x Load interaction. [c]Significant Footwear x Load interaction.

fitness by footwear interactions occurred on second maximum vertical force (Fz3), relative time to maximum antero-posterior braking force (Fy2), maximum plantarflexion velocity at the ankle (A3), maximum metatarsal flexion (Mt1), and maximum metatarsal flexion velocity (Mt3). The female data yielded a significant interaction between fitness and footwear on maximum antero-posterior braking force (Fy1), medio-lateral force excursions over 100% of the contact period (Fx2), maximum plantarflexion at the ankle (A1), and maximum metatarsal flexion (Mt1).

There were two interactions between footwear and load that were significant. Both occurred in analyses of the male data. The measures with a significant footwear by load interaction were maximum hip extension (H2) and maximum metatarsal flexion velocity (Mt3).

Table 4 also contains a summary of the significance levels of the main effects for each of the parameters measured during overground and treadmill walking. As indicated in the table, footwear had a significant main effect on many of the measures captured during walking. However, there were some categories of measures in which none of the parameters was significantly affected by footwear. For the men, these were the medio-lateral component of the ground reaction force, in-shoe pressure, activity of the rectus femoris and the gastrocnemius/soleus muscle groups, and the physiological measures. For the women, none of the parameters associated with the medio-lateral component of the ground reaction force, in-shoe pressure, and the activity of the medial hamstring, the anterior tibialis, and the gastrocnemius/soleus muscle groups reflected a significant main effect of footwear.

Findings related to the footwear main effect are presented in Table 5 for both the men and the women. The results of the post-hoc, *HSD* procedure applied to each footwear effect that was significant are included in the table. In the case of a significant effect, the footwear types with the highest and the lowest means, as determined by the *HSD* procedure, are indicated. Instances in which the footwear effect failed to reach significance are also indicated.

More detailed findings from the analyses of the walking parameters are presented in Appendix C. The odd-numbered tables in that appendix contain the data for the men and the even-numbered tables contain the data for the women.

Vertical Ground Reaction Force Component (Tables C-1 and C-2)

There were no significant second-order interactions on any of the vertical ground reaction force parameters. In addition, the interaction between footwear and load was not significant on any of the measures. There was, however, one significant interaction between footwear and fitness. This occurred in the analysis of the male data for second maximum force (Fz3). The means associated with this interaction are presented

Table 5. Extreme Values of Footwear Means for Overground and Treadmill Walking Parameters Based on Post Hoc Analyses of Footwear Main Effect

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
		Vertical Ground Reaction Force Component		
Fz1	Com, Jun, Nik, Roc	Ree, Red	Com, Jun, Ree, Nik, Roc	Red
Fz2	---	---	Com, Ree, Nik	Roc
Fz3	Ree, Nik	Com, Jun, Red	Ree, Nik, Roc	Com, Jun, Red
Fz4	---	---	---	---
Fz5	---	---	---	---
Fz6	Nik, Roc	Red	Nik, Roc	Com, Jun, Ree, Red
		Antero-posterior Ground Reaction Force Component		
Fy1[a]	Com, Jun	Ree, Nik	---	---
Fy2	Nik	Com, Jun, Ree, Roc, Red	Nik	Com, Red
Fy3	---	---	---	---
Fy4	---	---	---	---
Fy5	Jun	Nik, Roc	Com, Ree, Red	Nik, Roc
		Medio-lateral Ground Reaction Force Component		
Fx1	---	---	---	---
Fx2	---	---	---	---
		In-shoe Pressure		
P1	---	---	---	---
P2	---	---	---	---
P3	---	---	---	---

Table 5. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		Sagittal Plane Kinematics - Hip Angle		
H1	---	---	---	---
H2	---	---	---	---
H3	---	---	---	---
H4	Nik, Roc	Jun, Ree, Red	Nik	Com, Jun, Red
H5	---	---	---	---
H6	Nik, Roc	Red	---	---
		Sagittal Plane Kinematics - Knee Angle		
K1	Nik, Roc	Jun	Roc	Com
K2	---	---	---	---
K3	Nik, Roc	Com, Jun, Red	Roc	Com, Jun
K4	Nik, Roc	Com, Jun, Ree, Red	---	---
K5	---	---	Ree	Jun
K6	Nik, Roc	Com, Jun, Ree, Red	---	---
		Sagittal Plane Kinematics - Ankle Angle		
A1	Ree	Com, Jun, Nik, Roc, Red	Ree	Com, Jun, Nik, Roc, Red
A2[a]	Red	Ree	Com, Jun, Nik, Red	Ree
A3	Com, Jun, Red	Ree, Nik, Roc	Com, Jun, Red	Ree, Nik, Roc
A4	---	---	---	---
A5[a]	Ree, Nik	Com, Jun, Roc, Red	---	---
A6	---	---	Com, Nik	Roc

Table 5. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
	Sagittal Plane Kinematics - Metatarsal Angle			
Mt1	Ree, Nik, Roc	Com, Jun	Ree, Nik, Roc	Com, Jun, Red
Mt2	Nik, Roc	Com, Jun, Ree, Red	---	---
Mt3	Roc, Red	Com, Jun	Ree, Nik, Roc, Red	Jun
Mt4	Nik, Roc	Red	---	---
	Rearfoot Movement			
Rf1	Com, Jun, Roc	Nik	---	---
Rf2[a]	---	---	Com, Jun, Ree, Nik, Red	Roc
Rf3	Jun	Ree, Red	---	---
Rf4	---	---	Com, Jun, Red	Ree, Nik, Roc
Rf5[a]	---	---	Com, Red	Nik, Roc
	EMG - Medial Hamstring			
EMG1[a]	Jun, Nik, Roc	Com, Ree, Red	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
	EMG - Rectus Femoris			
EMG1	---	---	---	---
EMG2	---	---	Com	Roc
EMG3	---	---	---	---

Table 5. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		EMG - Anterior Tibialis		
EMG1	---	---	---	---
EMG2	Com	Jun, Ree, Nik, Roc, Red	---	---
EMG3	---	---	---	---
		EMG - Gastrocnemius/Soleus		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
		Physiological Measures		
M1	---	---	Nik	Red
M2	---	---	---	---
M3	---	---	---	---

Note. Dashes indicate a significance level of $p > .05$. Com = combat boot; Jun = jungle boot; Ree = Reebok Pump; Nik = Nike cross trainer; Roc = Rockport hiking boot; Red = Red Wing work boot.

[a]Values are highest and lowest absolute values.

graphically in Figure 9. The significant interaction appears to be attributable to greater differences among footwear means for the medium fitness group than for the other two fitness groups.

With regard to footwear main effects, the male data revealed that first maximum force (Fz1), second maximum force (Fz3), and total vertical impulse (Fz6) were significantly affected by the type of footwear worn. The values of first maximum force (Fz1) for the Reebok Pump and the Red Wing work boot were significantly higher than the values for the other footwear types. There were no other differences among the means. For second maximum force (Fz3), the highest mean value was associated with the combat boot. The mean for the combat boot differed significantly from the means for

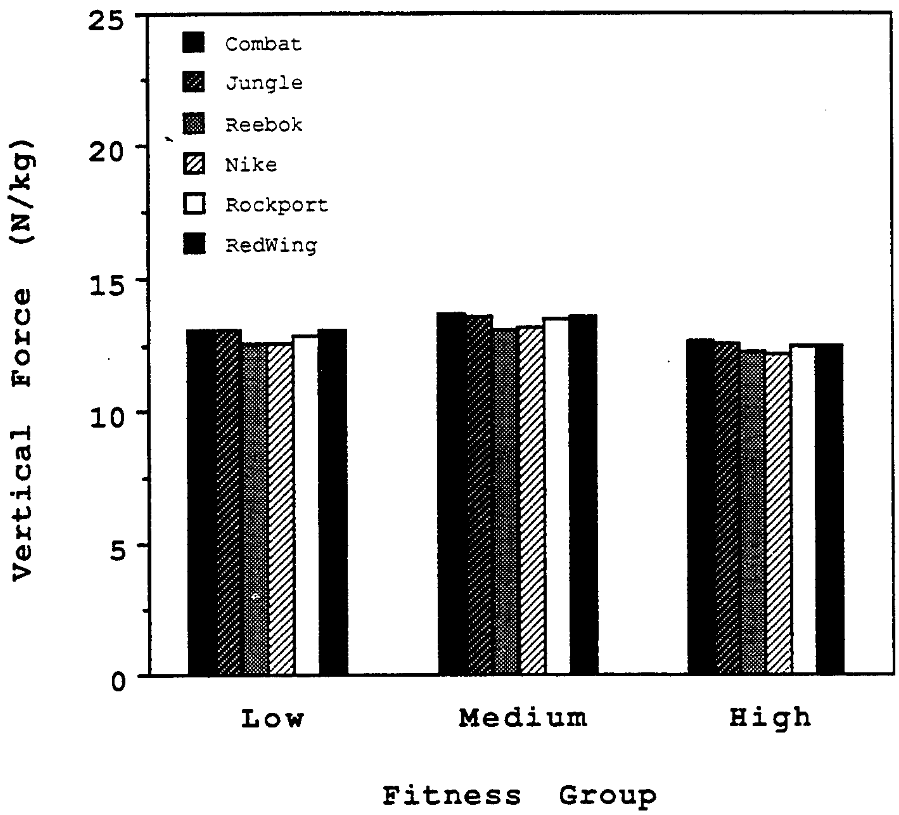

Figure 9. Means on second maximum force (Fz3), a vertical ground reaction force component, during walking under each footwear condition for men within each fitness group.

all other footwear types, with the exception of the jungle boot and the Red Wing. The values for the Reebok Pump and the Nike cross trainer were significantly lower than the values for the remaining footwear types. In terms of total vertical impulse (Fz6), the Red Wing work boot was associated with the highest mean. This value differed significantly from the means for the remaining footwear types. The Nike cross trainer and the Rockport hiking boot had means that were significantly lower than those for all other footwear. No other differences were significant on this parameter.

The female data yielded a significant effect of footwear on all parameters except relative time to second maximum force (Fz4) and average vertical force (Fz5). On first maximum force (Fz1), the value for the Red Wing was significantly higher than the values for the other footwear types, which did not differ. The shortest times to first maximum force (Fz2) were associated with the combat boot, the Reebok Pump, and the

Nike cross trainer. These times differed significantly from the longest time, that for the Rockport hiking boot. There were no other significant differences among the means. With regard to second maximum force (Fz3), the combat boot, the jungle boot, and the Red Wing had means that were significantly higher than those for the other footwear types. No other significant differences were obtained. In terms of total vertical impulse (Fz6), the lowest values, those for the Nike cross trainer and the Rockport hiking boot, were not significantly different from each other, but did differ significantly from the values for the remaining footwear types. There were no other significant differences on this parameter.

Antero-posterior Ground Reaction Force Component (Tables C-3 and C-4)

Analyses of the antero-posterior ground reaction force parameters did not yield any significant second-order interactions. Furthermore, footwear did not interact significantly with load on any of the measures. However, there were measures on which the interaction between footwear and fitness was significant.

Analyses of the male data yielded a significant interaction between footwear and fitness on relative time to maximum breaking force (Fy2). The means associated with this interaction are presented graphically in Figure 10. The significant finding appears to be attributable to the relatively low mean for the combat boot in the low fitness group and the relatively high mean for the boot in the other two fitness groups.

Analyses of the female data also yielded one significant interaction between footwear and fitness. This occurred on maximum braking force (Fy1); the interactions means are presented in Figure 11. In the figure, it can be seen that the footwear means for the medium fitness group are highly similar, whereas there were greater differences among footwear types reflected by the data of the low and the high fitness groups.

In terms of footwear main effects, the male data revealed a significant main effect for three parameters. On one of the parameters, maximum braking force (Fy1), the only significant differences were between the two forces of the largest magnitude and the two forces of the smallest magnitude. The Reebok Pump and the Nike cross trainer yielded forces of the largest magnitude; those for the combat and the jungle boots were the smallest. The men's time to maximum braking force (Fy2) was another parameter significantly affected by footwear. The lowest value, that for the Nike cross trainer, was significantly different from all other values. The remaining values did not differ. The third parameter found to be significantly affected by footwear in analyses of the male data was time to maximum propelling force (Fy5). The jungle boot yielded the lowest mean. The mean for the jungle boot differed significantly from the two highest means, which was associated with Nike cross trainer and the Rockport hiking boot. There were no other significant differences on this parameter.

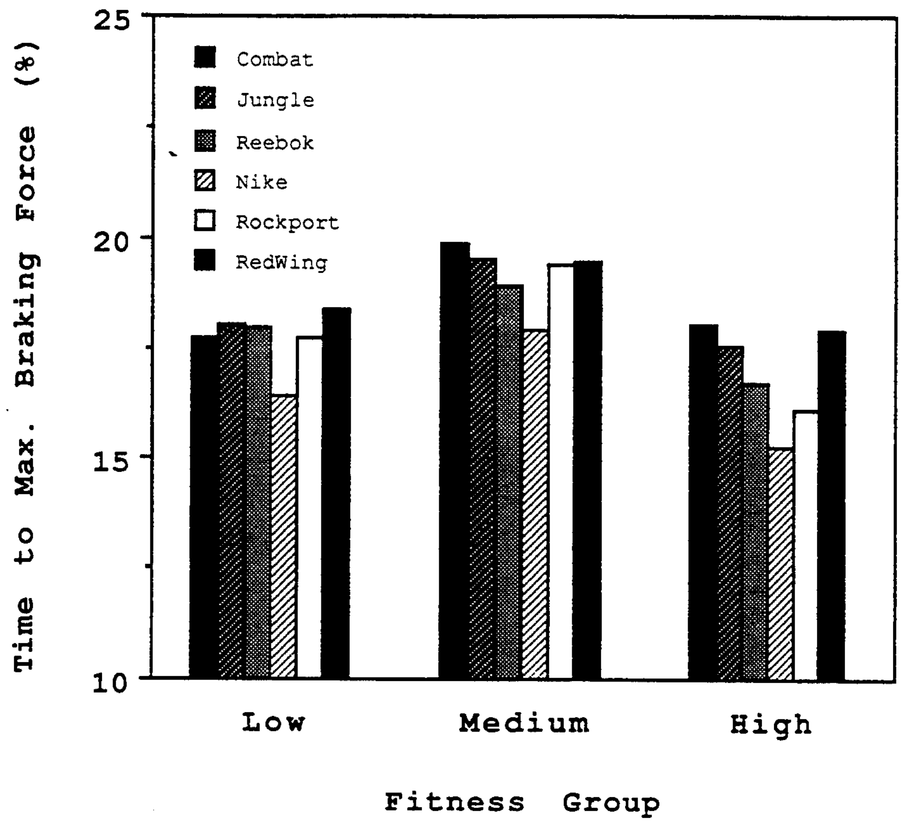

Figure 10. Means on relative time to maximum braking force (Fy2), an antero-posterior ground reaction force component, during walking under each footwear condition for men within each fitness group.

The female data revealed a significant effect of footwear on two parameters. One was time to maximum braking force (Fy2). Here, the lowest value, that for the Nike cross trainer, differed significantly from the values for the remaining footwear types. The highest values were for the combat boot and the Red Wing work boot. These values did not differ from each other, but were significantly different from the values for the other footwear. There were no other differences among footwear items. Time to maximum propelling force (Fy5) was the other parameter that yielded a significant footwear effect in the analyses of the female data. The means for the Nike cross trainer and the Rockport hiking boot did not differ from each other on this measure, but they were significantly higher than the means for all other footwear types. The combat boot, which yielded the lowest mean, also differed significantly from the jungle boot. There were no other differences among footwear items.

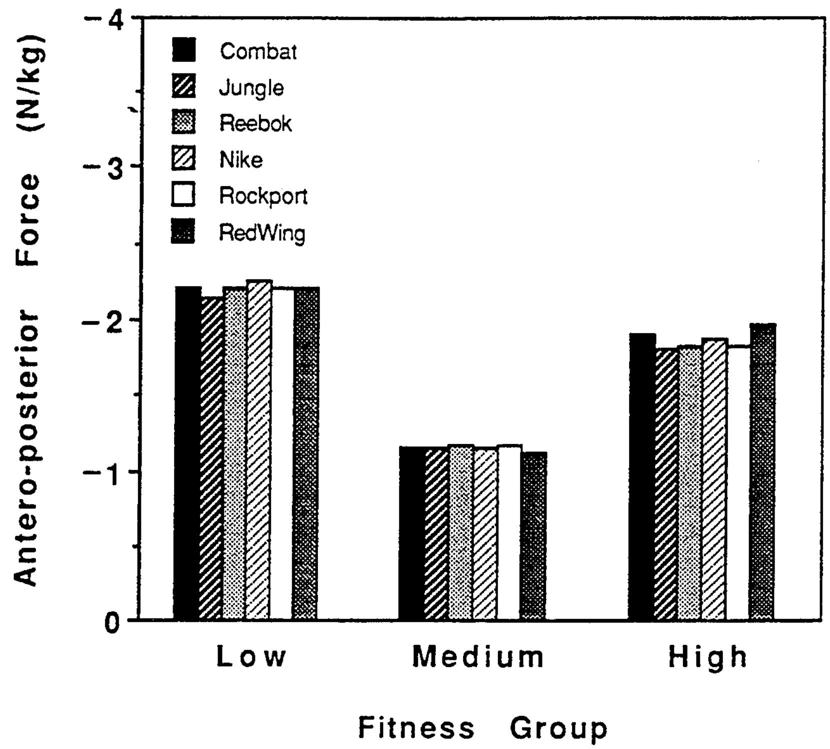

Figure 11. Means on maximum braking force (Fy1), an antero-posterior ground reaction force component, during walking under each footwear condition for women within each fitness group.

Medio-lateral Ground Reaction Force Component (Tables C-5 and C-6)

The main effect of footwear was not significant in any of the analyses of the medio-lateral ground reaction force measures and only one significant interaction involving footwear was obtained. This was the interaction between footwear and fitness in the analyses of the female data for force excursions 0-100% of the contact period (Fx2). The means for the interaction are presented graphically in Figure 12. It can be seen that, in the low fitness group, the mean for the Red Wing work boot is higher than the means for all other footwear types and the mean for the Rockport hiking boot is lower. In the other fitness groups, the means for the footwear types are highly similar to each other.

In-shoe Pressure (Tables C-7 and C-8)

The analyses of the in-shoe pressure data did not reveal any significant findings.

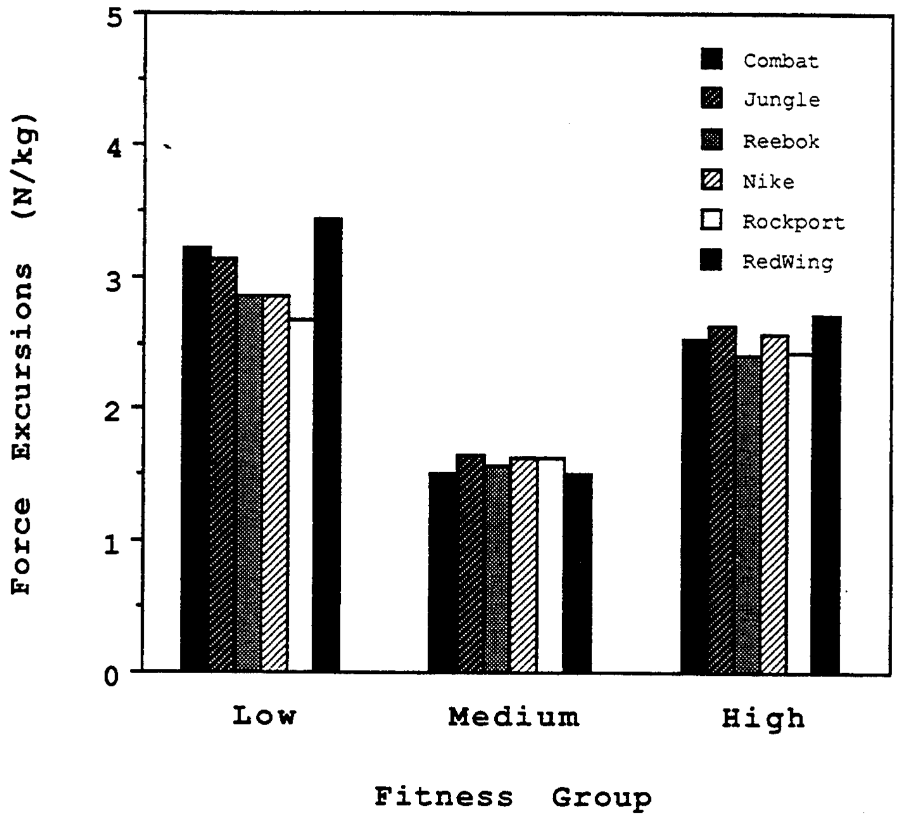

Figure 12. Means on force excursions 0-100% of contact period (Fx2), a medio-lateral ground reaction force component, during walking under each footwear condition for women within each fitness group.

Sagittal Plane Kinematics

Hip angle (Tables C-9 and C-10). Neither the male nor the female data revealed a significant second-order interaction on any of the hip angle parameters. In addition, there was only one significant first-order interaction involving footwear. This was an interaction between footwear and load obtained for the male maximum extension measure (H2). The significant interaction, which is presented graphically in Figure 13, appears to be attributable to the relatively high value for the Reebok Pump under the no-load and the 50-lb load conditions and its relatively low value under the 70-lb load. Similarly, the Nike cross trainer had a relatively low value under the no-load and the 50-lb load conditions and a relatively high value under the 70-lb load.

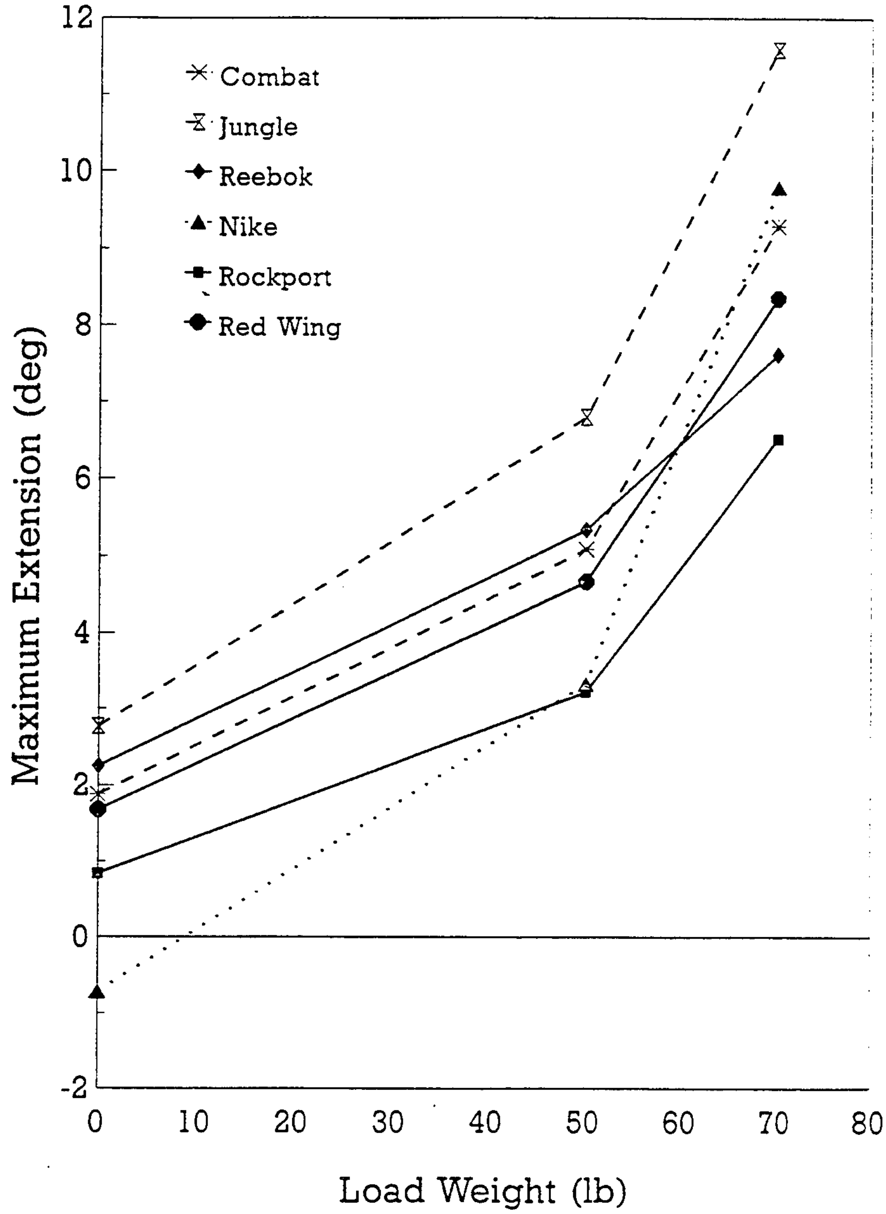

Figure 13. Means for men on maximum hip extension (H2) during walking under each footwear and load condition.

In terms of footwear main effects in analyses of the male data, time to maximum flexion velocity (H4) was one of two parameters significantly affected by footwear type. The shortest times were for the Nike cross trainer and the Rockport hiking boot. These values differed significantly from the longest times, which were for the jungle boot, the

Reebok Pump, and the Red Wing. The other parameter significantly affected by footwear in analyses of the male data was time to maximum extension velocity (H6). The shortest times were associated with the Nike cross trainer and the Rockport hiking boot. These times differed significantly from the longest times, which were for the Red Wing work boot.

The only parameter significantly affected by footwear in analyses of the female data was time to maximum flexion velocity (H4). The Nike cross trainer had the lowest mean. It differed significantly from the highest means. The highest means were those for the combat and the jungle boots and the Red Wing.

Knee angle (Tables C-11 and C-12). The second-order interaction was not found to be significant in the analyses of the knee angle data. Further, there were no significant first-order interactions involving footwear.

In terms of footwear main effects, the male data yielded significant findings on all parameters, except maximum extension (K2) and maximum extension velocity (K5). On the maximum flexion measure (K1), the jungle boot had the highest mean. This value differed significantly from the two lowest means, which were those for the Nike cross trainer and the Rockport hiking boot. There were no other significant difference among footwear items on this measure. On the maximum flexion velocity (K3) parameter, the combat boot, the jungle boot, and the Red Wing yielded the highest means. These means were significantly different from the lowest values, those for the Nike cross trainer and the Rockport hiking boot. No other significant differences were obtained on this parameter. The remaining two knee angle parameters significantly affected by footwear in the analyses of the male data revealed similar findings. On both time to maximum flexion velocity (K4) and time to maximum extension velocity (K6), times for the Nike cross trainer and the Rockport hiking boot were significantly faster than times for the remaining footwear items. There were no other significant findings on these two measures.

Analyses of the female data resulted in a significant footwear effect on three knee angle parameters. These were maximum flexion (K1), maximum flexion velocity (K3), and maximum extension velocity (K5). For the maximum flexion parameter (K1), the highest mean, that for the combat boot, was significantly different from the lowest, that for the Rockport hiking boot. No other significant differences were obtained on this measure. For maximum flexion velocity (K3), the value for the jungle boot was significantly higher than the values for all items except the combat boot. The mean for the Rockport hiking boot was significantly lower than the means for all other items. These were the only significant differences on this measure. On the maximum extension velocity (K5) parameter, the mean for the jungle boot was highest and it differed significantly only from the lowest mean, that for the Reebok Pump. No other differences were significant.

Ankle angle (Tables C-13 and C-14). No second-order interactions achieved significance for the ankle angle parameters. However, both the male and the female data revealed a significant interaction between fitness and footwear.

For the male data, fitness and footwear interacted significantly on the measure of maximum plantarflexion velocity (A3). The means for this interaction are presented in Figure 14. The significant interaction appears to be attributable to the fact that, for the low and the medium fitness groups, the combat boot had the lowest mean and, for the high fitness group, the Red Wing work boot had the lowest mean.

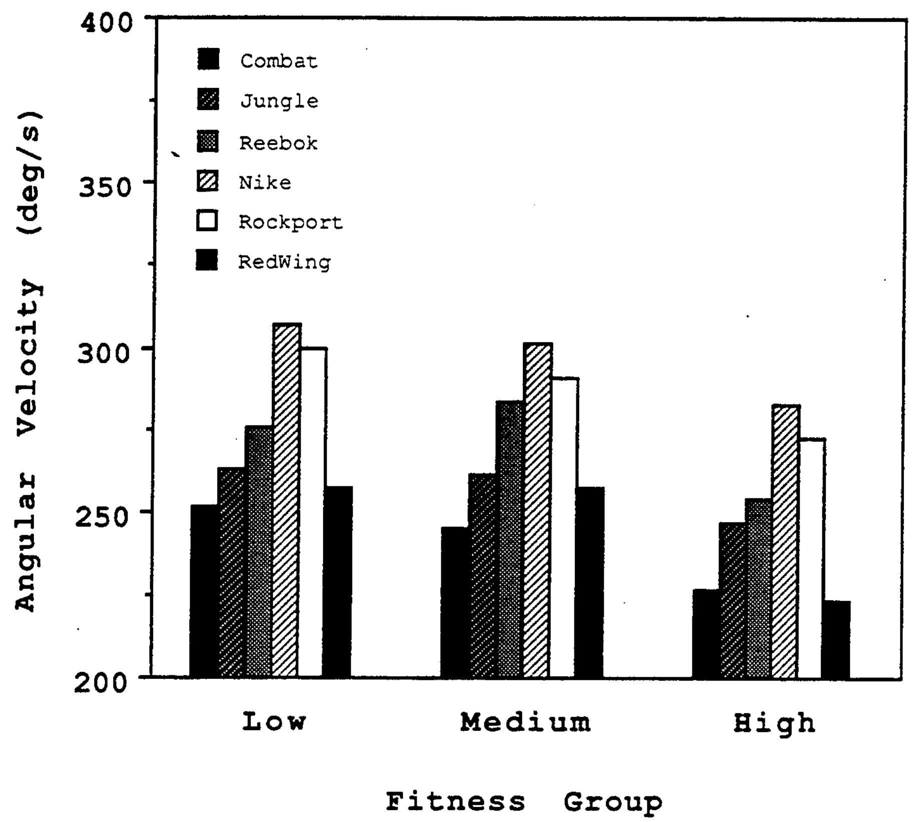

Figure 14. Means on maximum ankle plantarflexion velocity (A3) during walking under each footwear condition for men within each fitness group.

For the female data, a significant interaction between fitness and footwear occurred on the maximum plantarflexion measure (A1). The interaction means are presented in Figure 15. The significant finding appears to be attributable to the fact that, in the low fitness group, the Red Wing work boot had the highest mean and, in the other two fitness groups, the jungle boot had the highest mean.

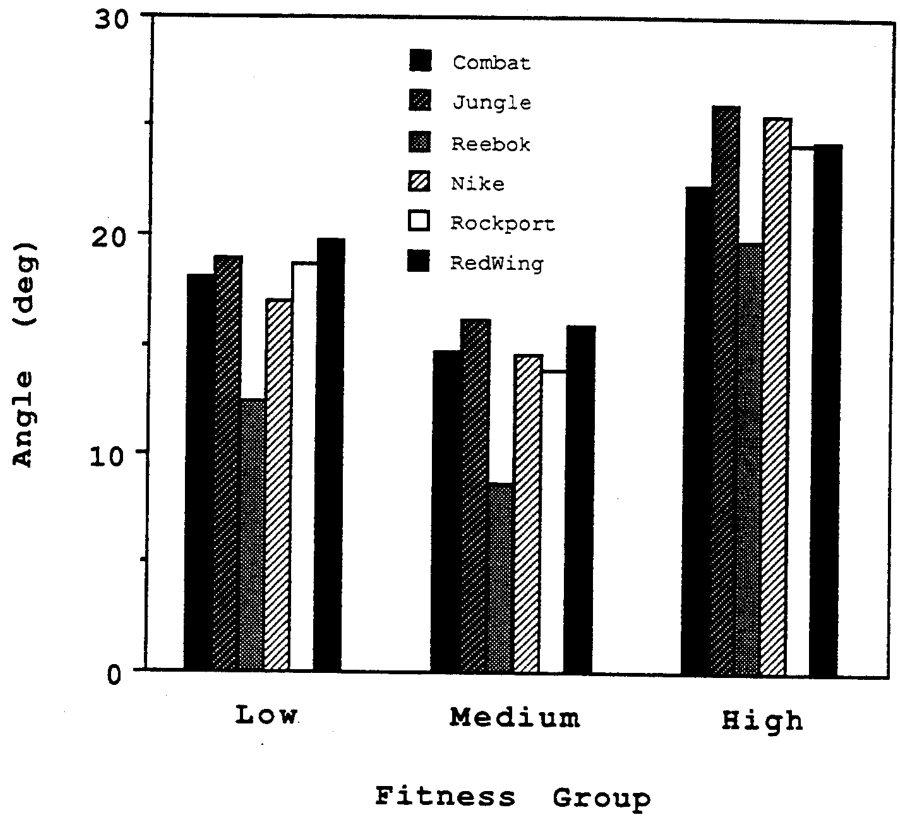

Figure 15. Means on maximum ankle plantarflexion (A1) during walking under each footwear condition for women within each fitness group.

In terms of the main effect of footwear on ankle angle parameters, analyses of the male data revealed significant findings for all parameters except time to maximum plantarflexion velocity (A4) and time to maximum dorsiflexion velocity (A6). For the maximum plantarflexion variable (A1), the lowest mean was achieved with the Reebok Pump. It was significantly different from the means for the other footwear types, which did not differ. For maximum dorsiflexion (A2), a negative quantity, the largest and the smallest absolute values differed significantly from each other and from the remaining means. The largest absolute value was for the Reebok Pump and the smallest for the Red Wing work boot. On the maximum plantarflexion velocity measure (A3), the three lowest values, those for the combat boot, the jungle boot, and the Red Wing, were significantly different from the values for the remaining three footwear types. There were no other significant differences on this measure. With regard to maximum dorsiflexion velocity (A5), a negative quantity, the absolute values for the Reebok Pump and the Nike Cross Trainer were significantly smaller than the values for the other footwear items. There were no other significant differences on this measure.

Analyses of the female data revealed a significant main effect of footwear on all parameters except time to maximum plantarflexion velocity (A4) and maximum dorsiflexion velocity (A5). On the maximum plantarflexion parameter (A1), the lowest mean, which was achieved with the Reebok Pump, differed significantly from the remaining means. No other differences were significant on this measure. For maximum dorsiflexion (A2), a negative quantity, the largest absolute value was achieved with the Reebok Pump. The mean for this footwear was significantly different from the means for the other footwear types. The smallest absolute value, which was achieved with the Red Wing, also differed significantly from the value for the Rockport hiking boot. On the maximum plantarflexion velocity measure (A3), the mean for the combat boot, which was the lowest mean, did not differ from the means for the jungle boot and the Red Wing, but it was significantly different from the means for the remaining footwear types. Similarly, the highest mean, which was achieved with the Nike cross trainer, did not differ from the means for the Reebok Pump and the Rockport hiking boot, but it was significantly higher than the means for the remaining footwear types. On the time to maximum dorsiflexion velocity (A6), the fastest times were achieved with the combat boot and the Nike cross trainer. These times differed significantly from the slowest time, which was for the Rockport hiking boot. There were no other significant findings for this parameter.

Metatarsal angle (Tables C-15 and C-16). There were no significant second-order interactions in the analyses of the metatarsal angle parameters, but there were several significant first-order interactions between fitness and footwear.

The male data yielded a significant interaction between fitness and footwear on maximum flexion (Mt1) and maximum flexion velocity (Mt3). The significant interaction on maximum extension is presented in Figure 16. This interaction appears to be attributable to the fact that the mean for the combat boot was highest in the high fitness group and the mean for the jungle boot was highest in the other fitness groups.

The other significant interaction between fitness and footwear revealed in analyses of the male data, which is presented graphically in Figure 17, occurred on maximum flexion velocity (Mt3). The significant finding appears to be attributable to the fact that,

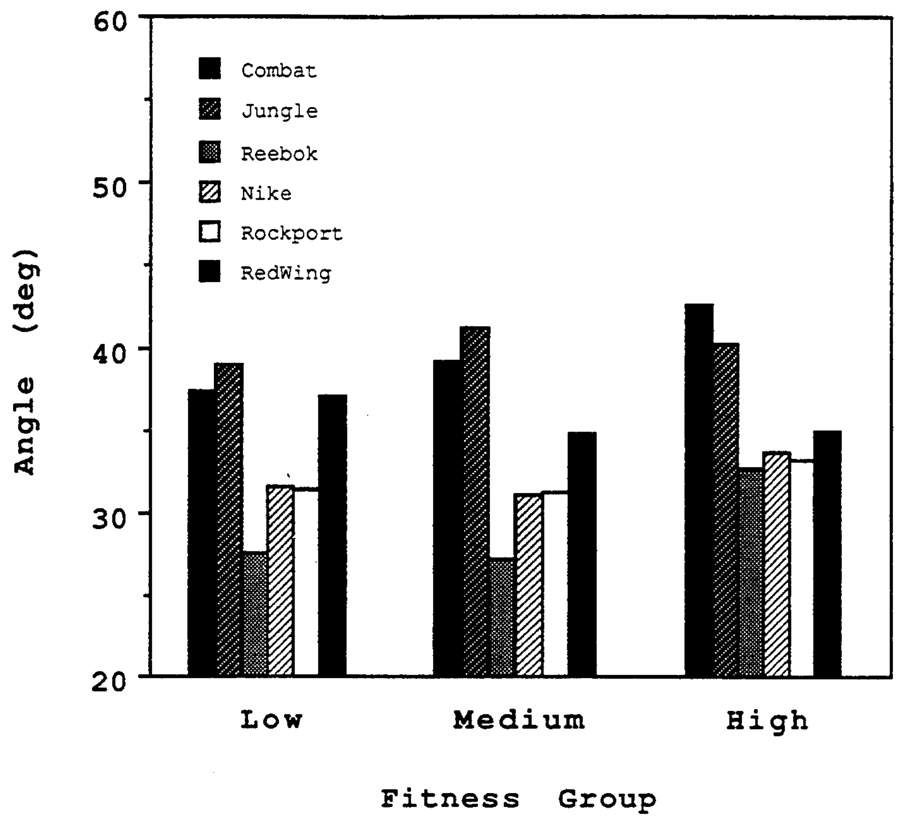

Figure 16. Means on maximum metatarsal flexion (Mt1) during walking under each footwear condition for men within each fitness group.

for the low and the high fitness groups, the highest mean was for the combat boot; for the medium fitness group, the means for the combat and the jungle boots were highest and were approximately equal to each other.

Analyses of the female data revealed one significant interaction between fitness and footwear. The significant finding was on the maximum flexion measure (Mt1), and the interaction means are presented graphically in Figure 18. The interaction appears to be attributable to the fact that, in the high and the low fitness groups, the mean for the Reebok Pump was lower than the means for all other footwear types, whereas, in the medium fitness group, the Nike cross trainer and the Rockport hiking boot, along with the Reebok Pump, had the lowest means, and these were approximately equal to each other.

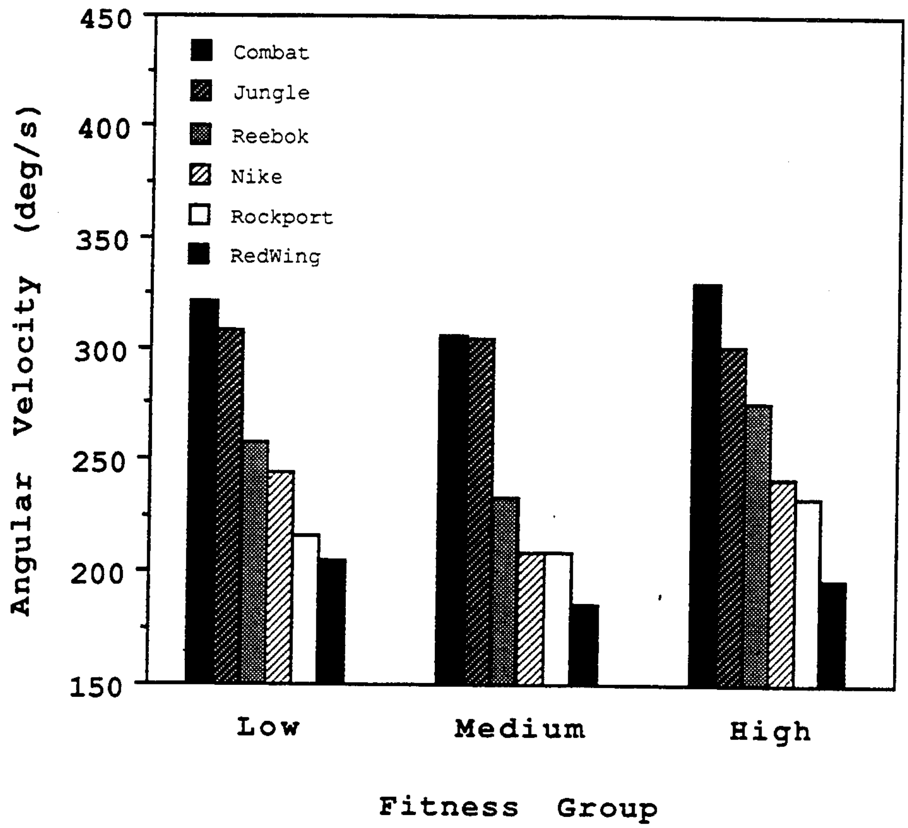

Figure 17. Means on maximum metatarsal flexion velocity (Mt3) during walking under each footwear condition for men within each fitness group.

There was also one significant interaction between footwear and load in the analyses of the metatarsal angle data. This was for the male maximum velocity measure (Mt3). The interaction means are presented graphically in Figure 19. The interaction appears to be attributable to the small increases in the values for the jungle boot, the Reebok Pump, and the Red Wing, relative to the other footwear types, as load increased from 50 lb to 70 lb.

In terms of footwear main effects, all parameters were found to be significant in the analyses of the male data. With regard to maximum flexion (Mt1), the lowest means were obtained with the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. These means were significantly different from the means for all other footwear items. The means for the combat and the jungle boots were significantly higher than all others. For the time to maximum flexion measure (Mt2), the Nike cross trainer and the Rockport hiking boot had values that were significantly lower than those for the remaining footwear types. There were no other significant differences on this measure.

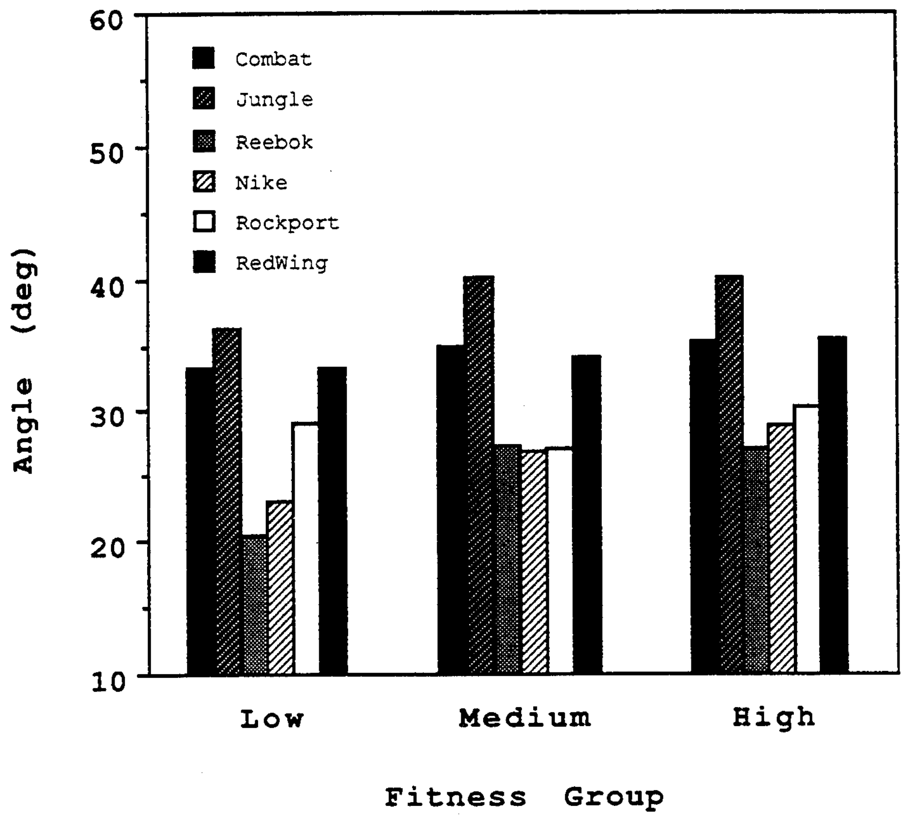

Figure 18. Means on maximum metatarsal flexion (Mt1) during walking under each footwear condition for women within each fitness group.

On the maximum velocity parameter (Mt3), the combat and the jungle boots yielded the highest values. The means for these two footwear types did not differ from each other, but they were significantly different from the means for the other footwear. The lowest value, which was associated with the Red Wing work boot, differed significantly from all others, except the value for the Rockport hiking boot. No other significant findings were obtained on this measure. With regard to time to maximum velocity (Mt4), the fastest times were achieved with the Nike cross trainer. The mean differed significantly from all others, except that for the Rockport hiking boot. The slowest times were associated with the Red Wing work boot. The mean for the Red Wing differed significantly from the means for the remaining footwear. No other differences on this parameter were significant.

The analyses of the female data yielded significant footwear effects on two parameters, maximum flexion (Mt1) and maximum velocity (Mt3). On maximum

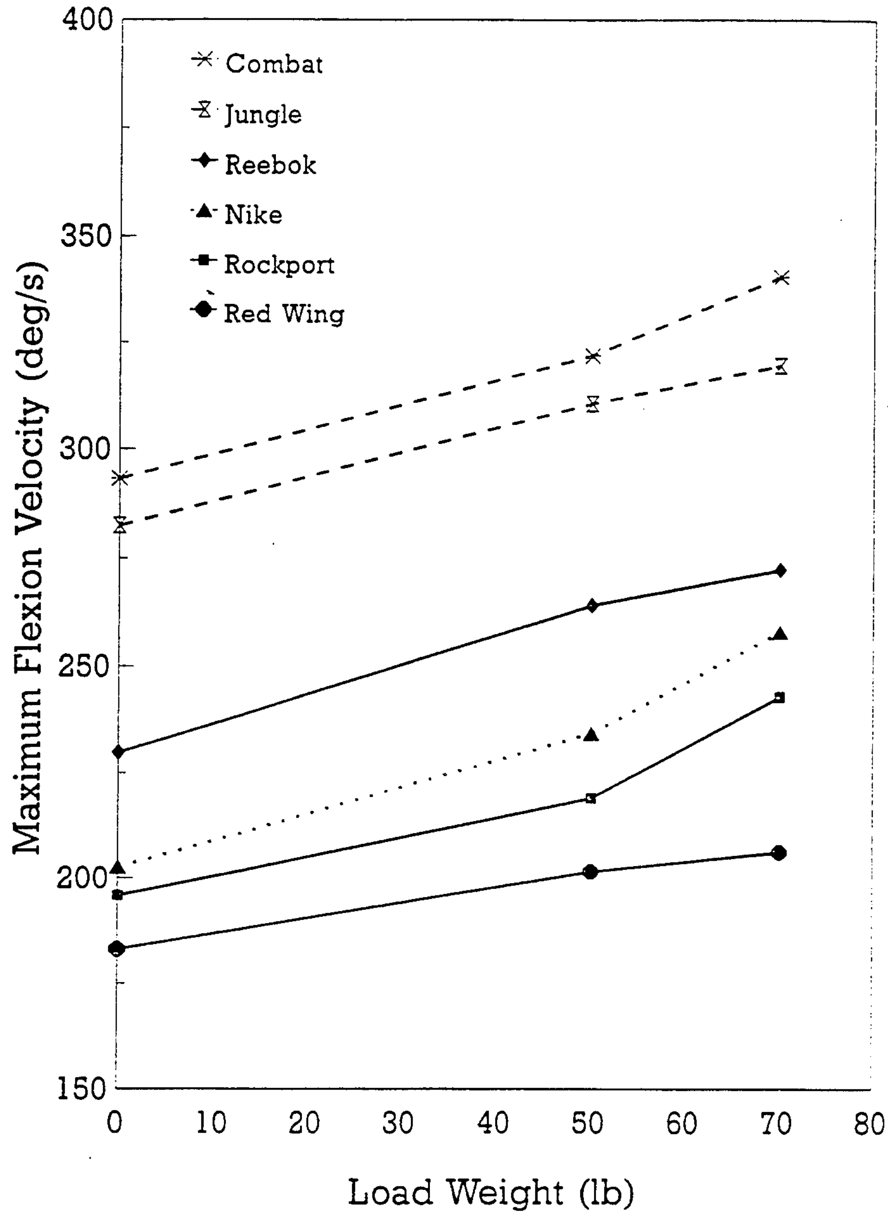

Figure 19. Means for men on maximum metatarsal flexion velocity (Mt3) during walking under each footwear and load condition.

flexion, the means for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot were significantly lower than the means for the remaining three footwear conditions. There were no other significant findings on this measure. With regard to maximum velocity (Mt3), the value for the jungle boot was significantly higher than the values for the remaining footwear types, with the exception of the combat boot value. The lowest means were achieved with the Rockport hiking boot and the Red Wing. These means differed significantly from those for the combat and the jungle boots. This was the extent of the significant differences on this parameter.

Rearfoot Movement (Tables C-17 and C-18)

The analyses of the rearfoot movement parameters did not reveal any significant interactions. However, there were several instances in which a significant main effect of footwear was obtained.

Analyses of the male data yielded a significant main effect of footwear on two rearfoot movement parameters. One of these was rearfoot angle at foot strike (Rf1). Here, the means for the combat boot, the jungle boot, and the Rockport hiking boot did not differ from each other, but were significantly lower than the means for the other footwear conditions. The highest mean, that for the Nike cross trainer was significantly different from the means for all other footwear types. There were no other significant differences on this measure. The second parameter reflecting a significant footwear effect in the analyses of the male data was time to maximum rearfoot angle (Rf3). The fastest time, that for the jungle boot, was significantly different from the two slowest times, those for the Reebok Pump and the Red Wing. No other significant findings were obtained on this measure.

Analyses of the female data yielded significant effects of footwear on three parameters. For maximum rearfoot angle (Rf2), a negative quantity, the absolute value for the Rockport hiking boot was significantly greater than the values for the remaining footwear types. There were no other significant differences on this measure. For total rearfoot motion (Rf4), the three lowest and the three highest means differed significantly. The three lowest means were associated with the combat boot, the jungle boot, and the Red Wing. For maximum rearfoot velocity (Rf5), a negative quantity, the absolute values for the combat boot and the Red Wing were significantly smaller than the values for the remaining footwear types. The means for the Nike cross trainer and the Rockport hiking boot were significantly larger than all other means. There were no further significant differences on this parameter.

EMG

Medial hamstring (Tables C-19 and C-20). Analyses of the medial hamstring parameters did not yield any significant interactions and there was only one instance in which the main effect of footwear was significant; the male data revealed a significant footwear effect on time of onset of muscle activity (EMG1). With the combat boot, the

Reebok Pump, and the Red Wing, muscle activity began significantly earlier, relative to foot strike, than it did with the remaining footwear types.

Rectus femoris (Tables C-21 and C-22). Analyses of rectus femoris measures did not yield any significant interactions involving footwear, and footwear had a significant main effect only on the female data. This was a significant footwear effect on time of termination of muscle activity (EMG2). The earliest termination of activity occurred with the combat boot and the latest with the Rockport hiking boot. The means for these two conditions differed significantly. There were no other significant findings on this measure.

Anterior tibialis (Tables C-23 and C-24). There were no significant interactions in the analyses of anterior tibialis activity, but there was one significant main effect of footwear. This occurred on the termination of muscle activity measure (EMG2) for the men. Activity terminated significantly earlier with the combat boot than it did with the other footwear items. There were no other significant differences among footwear types on this measure.

Gastrocnemius/soleus (Tables C-25 and C-26). Analyses of the parameters involving activity of the gastrocnemius/soleus muscle group did not yield any significant interactions or significant main effects of footwear.

Physiological Measures (Tables C-27 and C-28)

None of the analyses of the physiological measures yielded significant interactions and there was only one instance in which a significant footwear main effect was obtained. This was in the analysis of the female data for oxygen uptake (M1). Here, only the lowest and the highest means differed significantly. The lowest mean was achieved with the Nike cross trainer and the highest with the Red Wing.

Discussion

The impact test data collected during the materials testing phase of this research revealed substantially higher values of peak g for the military boots than for the Nike cross trainer (Hamill and Bensel, 1992). This finding was not reflected in the data for the vertical ground reaction force component during overground walking insofar as the military boots did not differ significantly from the Nike cross trainer with regard to the magnitude of the first maximum force, or impact peak. Both the male and the female data revealed that the magnitude of first maximum force was greatest with the Red Wing work boot. This result is not unexpected in light of the peak g data on the impact test, where the values for the Red Wing work boot, although not as high as those for the military boots, were higher than those for the other commercial items.

It was in the magnitude of the second maximum vertical force, the thrust or propulsive peak, that the military boots were differentiated from the Nike cross trainer. On this measure, the forces of the highest magnitude, significantly higher than the force with the Nike cross trainer, were observed with the military boots and the Red Wing work boot. Analyses of the male data revealed that, along with the Nike cross trainer, the Reebok Pump was associated with low magnitudes of force. For the female data, the lowest values were achieved with these two footwear types and with the Rockport hiking boot.

The military boots were also differentiated from the Nike cross trainer on the parameter of total vertical force impulse, a measure summarizing the vertical force-time history. Both the male and the female data revealed that the highest values were associated with the Red Wing work boot, followed by the military boots; the lowest values were associated with the Nike cross trainer and the Rockport hiking boot. In the case of the female data, the lowest values differed significantly from all others. For the male data, only the highest value, that for the Red Wing work boot, differed significantly from the two lowest values.

On the impact test, the shortest times to peak g were associated with the military boots (Hamill and Bensel, 1992). The vertical ground reaction force data during overground walking reflected this finding to only a limited extent. For the men, time to first maximum force did not differ significantly as a function of footwear. For the women, a significant footwear effect was obtained, and the combat boot yielded one of the shortest times to first maximum force. However, the value for the combat boot was significantly different only from the highest value, that for the Rockport hiking boot. With regard to time to second maximum force, a significant footwear effect was not obtained in the analysis of either the male or the female data.

The materials testing revealed higher peak pressures for the military boots than for the commercial items (Hamill and Bensel, 1992). However, the analyses of in-shoe measurements of peak heel and peak forefoot pressures during overground walking did not yield a significant footwear effect.

When only impact peak, or first maximum vertical force, and peak in-shoe pressures are considered, the performance of the military boots during overground walking was better than expected given the results of the materials testing; the military boots yielded values that were comparable to those for the other footwear items, including the Nike cross trainer. However, the vertical forces recorded over the time of ground contact indicate that the military boots and the Red Wing work boot did not absorb the forces as effectively as some of the other items tested did, particularly the Nike cross trainer.

In the materials testing phase, Hamill and Bensel (1992) found that the foreparts of the military boots and the Red Wing work boot were not as flexible those of the other footwear items tested. Given this finding, the military boots and the Red Wing work boot would be expected to be associated with higher levels of muscle activity than the other three footwear types because of greater muscular involvement in bending the foot and the shoe. However, footwear did not have a significant effect on the amplitude of the signal from any of the four muscle groups recorded during overground walking. From the metatarsal joint angle data, it appears that, to propel the body forward into the next step, the foot was bent at the metatarsals to a greater extent in the military boots and the Red Wing Work boot, the footwear found to be the stiffest on the materials test, than it was in the more flexible footwear. This finding was revealed on the maximum metatarsal flexion parameter. For both the male and the female data sets, the largest angles, indicating the greatest amount of forefoot flexion, were associated with the military boots and the Red Wing work boot. The values for these footwear items differed significantly from the values for the three remaining footwear types.

The analyses of the male and the female data for maximum metatarsal flexion yielded a significant interaction between fitness and footwear. However, for both genders and all fitness groups, the three highest values were associated with the military boots and the Red Wing work boot and the three lowest values were associated with the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot.

On the maximum metatarsal flexion velocity parameter, the values for the military boots were relatively high. Thus, with the military boots, metatarsal flexion described a relatively large angular excursion at the joint and involved a high velocity movement.

In their assessment of rearfoot stability in the materials testing phase of this research, Hamill and Bensel (1992) found that the military boots, along with the Red Wing work boot, had the highest stability scores and that the Reebok Pump had the lowest. The data on rearfoot movement during overground walking reflected the results from the materials testing to some extent. Footwear had a significant effect on total rearfoot motion in the analysis of the female, but not the male, data. For the female data, the military boots and the Red Wing work boot were associated with the three smallest angular excursions, indicating relatively small amounts of angular movement of the calcaneus relative to the lower leg over the period of ground contact. Thus, the female results on the total rearfoot motion parameter were as expected from the materials testing. However, in terms of the maximum rearfoot angle parameter, the male data again did not yield a significant footwear effect and the female results, although significant, revealed a difference between the highest score, that for the Rockport hiking boot, and the scores for the remaining footwear types, which did not differ significantly from each other. These data for the rearfoot movement parameters recorded during overground walking provide only limited evidence that the military boots and the Red Wing work boot are associated with less subtalar joint pronation than such commercial items as the Nike cross trainer or the Reebok Pump.

Up to this point in the discussion, the focus has been on parameters recorded during walking that may be associated with parameters assessed in the materials testing (Hamill and Bensel, 1992). However, there were measures made during walking that do not parallel those made in the materials testing, but that do serve to further describe locomotor patterns during walking. Among the measures were those of the antero-posterior component of ground reaction force. Although the vertical component of ground reaction force is larger in magnitude and the one that the impact test is designed to investigate, the antero-posterior component is also of interest because of the resultant shear stress on the foot and footwear, as opposed to compressive stress (Cavanagh and Lafortune, 1980; Cavanagh et al., 1984).

Footwear significantly affected several of the antero-posterior ground reaction force variables. In the analysis of the male data, footwear had a significant effect on maximum braking force, which reflects the slowing down of the body relatively early in the ground contact period. The forces of the smallest amplitude were associated with the military boots. These differed significantly from the forces of the largest amplitude, which were associated with the Reebok Pump and the Nike cross trainer. In the analysis of the female data for maximum braking force, the main effect of footwear was not significant, but the interaction between footwear and fitness group was. In the low fitness group, the largest force amplitude was for the Nike cross trainer; in the medium fitness group, the values for the footwear types were essentially equal; and, in the high fitness group, the largest force amplitude was for the Red Wing work boot. Neither the male nor the female data revealed a significant effect involving footwear on maximum propelling force, the force associated with forward acceleration of the body relatively late the during ground contact period.

In the analyses of both the male and the female data sets, the relative time to maximum braking force was significantly affected by the footwear being used. In the case of the men, there was a significant interaction between footwear and fitness group. For the low fitness group, the times for the Red Wing work boot were longer than those for the other footwear types and, for the other fitness groups, the combat boot resulted in the longest times. However, regardless of fitness group, the shortest times were associated with the Nike cross trainer. For the women, the times with the Nike cross trainer were significantly shorter than the times with the other footwear types; the longest times were associated with the Red Wing work boot, followed by the combat boot.

Footwear did not differentially impact relative time to transition force, but it did significantly affect relative time to maximum propelling force. The male and the female data revealed that the longest times were associated with the Nike cross trainer and the Rockport hiking boot. In the case of the men, the times for these footwear types differed significantly from the shortest time, which was achieved with the jungle boot. For the women, the combat boot resulted in the shortest time to maximum propelling force.

Contrasting the military boots with the Nike cross trainer, these force and time data indicate that the braking forces were of lower magnitude and tended to occur later in the ground contact period with the military boots. These findings reflect positively on the military boots insofar as the shear stress associated with braking was less than that with the Nike cross trainer and the forces were applied over a longer time. On the other hand, although all footwear types yielded approximately equal magnitudes of propelling force, the propelling forces tended to occur earlier in the ground contact period with the military boots than with the Nike cross trainer.

Other parameters recorded during walking that do not parallel those assessed in the materials testing, but do further describe the walking movement are knee angle variables derived from the sagittal plane kinematics. One of the knee angle measures is maximum knee flexion.

For the male data, the largest knee flexion angle, indicating the greatest extent of flexion, was associated with the jungle boot. The angle for the jungle boot differed significantly from the smallest angles, which were for the Nike cross trainer and the Rockport hiking boot. The maximum knee flexion angles for the combat boot and for the Reebok Pump were also relatively large, but they did not differ from the smallest angles. For the female data, the combat boot resulted in the largest knee flexion angle. The smallest angle, which was for the Rockport hiking boot, differed significantly from the angle for the combat boot. In addition, the jungle boot was associated with the largest knee flexion angle next to that for the combat boot. However, the value for the jungle boot did not differ from the values for any of the other footwear.

On a second knee angle measure, maximum flexion velocity, the male and the female data revealed that the highest velocities occurred when the military boots and the Red Wing work boot were being worn. Analyses of the male data yielded a significant difference between these three highest and the two lowest velocities, which were for the Nike cross trainer and the Rockport hiking boot. The analyses of the female data revealed that the value for the jungle boot differed significantly from the values for both the Nike cross trainer and the Rockport hiking boot; the values for the combat boot and the Red Wing work boot, though high, differed significantly from the value for the Rockport hiking boot, but not from the value for the Nike cross trainer.

The findings related to metatarsal joint angles indicated that, compared with the other footwear tested, use of the military boots and the Red Wing work boot was characterized by greater angular excursions about the joint at higher velocities to propel the body forward into the next step. The results for the knee joint angle parameters show that the military boots and the Red Wing work boot were also characterized by greater involvement of the knee during the swing phase, in terms of both the degree and the velocity of knee flexion. The data for the ankle angle parameters further differentiated the military boots and the Red Wing work boot from the other items studied.

It would seem that the extent of ankle plantarflexion and dorsiflexion would be influenced by the height of the footwear upper, the flexibility of the materials comprising the upper, and the design and fit of the upper about the ankle and the lower leg. All footwear tested extended at least to the level of the lateral malleolus. The three footwear types with the highest uppers were, in descending order of height, the combat boot, the jungle boot, and the Red Wing work boot. These were followed, again in descending order of height, by the Reebok Pump, the Rockport hiking boot, and the Nike cross trainer.

In the analyses of both the male and the female data, there was a significant effect of footwear on maximum plantarflexion angle, which occurs after toe-off, early in the swing phase. However, the extent of angular excursion at the ankle did not vary directly with upper height of the footwear. For the male data, the lowest maximum plantarflexion value occurred with the Reebok Pump; the highest occurred with the jungle boot, followed by the Red Wing work boot and the Nike cross trainer. The female data yielded a significant interaction between footwear and fitness group on this measure. However, the findings were similar to those obtained on the male data. For every fitness group, the Reebok Pump had the lowest maximum plantarflexion values. With regard to the highest values, the low fitness group evidenced the largest angular excursions with the Red Wing work boot and the other two fitness groups had the largest angular excursions with the jungle boot.

Maximum plantarflexion velocity varied with upper height of the footwear in a more ordered fashion than maximum plantarflexion did. Analysis of the male data yielded a significant interaction between footwear type and fitness group. In both the low and the medium fitness groups, velocity increased as upper height decreased with the exception of lower values for the Red Wing work boot than for the jungle boot. Similar results were obtained for the high fitness group, with the exception of the fact that the value for the Red Wing work boot was somewhat lower than the values for both the combat and the jungle boots. In the analysis of the female data as well, velocity generally increased as upper height decreased. There was the exception that the value for the Red Wing work boot was greater than the value for the jungle boot, although the height of the Red Wing work boot was less than that of the jungle boot.

Maximum dorsiflexion angle, which occurs during the ground contact phase, was also significantly affected by footwear in the analyses of both the male and the female data sets. As was the case with plantarflexion angle, the extent of angular excursion did not vary directly with footwear upper height. For example, in both the male and the female data sets, the smallest maximum dorsiflexion angle occurred with the Red Wing work boot and the largest with the Reebok Pump. However, the three smallest maximum angles were associated with the three footwear types with the highest uppers and the three largest angles were associated with the three footwear types with the lowest uppers. Thus, there was some indication that height of the upper affected the extent of dorsiflexion.

The analysis of the male, but not the female, data for maximum dorsiflexion velocity yielded a significant footwear effect. As was the case with dorsiflexion angle, velocity did not vary in an ordered fashion with upper height. However, the greatest negative magnitudes of joint angular velocities, indicating increased loading on the ankle joint, were associated with the military boots and the Red Wing work boot, the three footwear types with the highest uppers. Therefore, there was some indication that height of the upper affected dorsiflexion velocity.

Another physical characteristic of footwear, its mass, is a factor that researchers have found may affect oxygen uptake and heart rate (Jones et al., 1984; Jones et al., 1986; Martin, 1985). Although the military boots were the heaviest footwear items tested, there was no evidence from the analyses of the oxygen consumption or the heart rate measures that the energy cost of walking in these boots was greater than the cost of walking in the lightest footwear, the Nike cross trainer. The only significant finding occurred in the analysis of the female data for oxygen consumption. On this parameter, the highest value, which was achieved with the Red Wing work boot, differed significantly from the lowest, which was achieved with the Nike cross trainer. No other differences between footwear items were significant.

Thus, as was the case with the measures of muscle activity, the measures of energy cost during walking did not differentiate between the military boots and the other footwear types. However, the combat and the jungle boots did differ from the Nike cross trainer and other footwear on a number of the parameters recorded during walking. Considering the overall findings for walking, it appears that the combat and the jungle boots did not absorb vertical ground reaction forces as effectively as some of the other footwear tested did. In terms of antero-posterior ground reaction force variables, braking forces were of lower magnitude and tended to occur later in the support phase with the military boots, whereas the propelling forces tended to occur earlier. Furthermore, the military boots were associated with extensive flexion at the knee that occurred at a relatively high velocity. Data for the metatarsal joint indicated greater angular excursions about the joint occurring at higher velocities with the military boots. Ankle dorsiflexion was limited with the military boots and had relatively large negative magnitudes of angular velocity. In addition, there was some evidence, mainly in the women's performance during walking, that there was less movement of the calcaneus relative to the lower leg when the military boots were used compared with some of the other footwear types.

Overground and Treadmill Marching (1.50 m/s)

Results

Summary

Interactions found to be significant in the analyses of the male and the female data for marching are indicated in Table 6. As was the case for walking, the analyses of the parameters for marching did not reveal any significant second-order interactions. However, there were significant first-order interactions involving footwear. Both the male and the female data revealed significant interactions between fitness and footwear and between footwear and load. For the men, the significant fitness by footwear interactions were obtained on the measures of maximum metatarsal flexion (Mt1), maximum metatarsal velocity (Mt3), and area under the curve for activity of the medial hamstring (EMG3). The significant interactions between fitness and footwear in the analyses of the female data occurred on maximum antero-posterior braking force (Fy1), medio-lateral force excursions during the initial 30% (Fx1) and during the entire (Fx2) contact period, maximum plantarflexion at the ankle (A1), maximum flexion (Mt1) and maximum velocity (Mt3) at the metatarsals, and time to onset of activity of the gastrocnemius/soleus muscle group (EMG1).

With regard to the interaction between footwear and load, the male data revealed significant findings on only one measure, maximum plantarflexion velocity at the ankle (A3). The female data yielded significant interactions between footwear and load on relative time to transition of the antero-posterior force component (Fy3), maximum hip extension (H2), and maximum hip flexion velocity (H3).

A summary of the significance levels of the main effects for each of the marching parameters is presented in Table 6. As indicated in the table, footwear had a significant main effect on many of the measures captured during marching, as it had during walking. However, there were again some categories of measures in which none of the parameters

Table 6. Significance of Main Effects and Summary of Significant Interactions in the Analyses of Overground and Treadmill Marching Parameters

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Vertical Ground Reaction Force Component			
Fz1	--- [b]	--- [b]	.005	.005	.001 [b]	.001 [b]
Fz2	---	---	.001	.001	---	---
Fz3	--- [b]	--- [b]	.001	.001	.001 [b]	.001 [b]
Fz4	---	---	---	.005	.001	---
Fz5	--- [b]	--- [b]	---	.001	.001 [b]	.001 [b]
Fz6	--- [b]	--- [b]	---	---	.001 [b]	.001 [b]
			Antero-posterior Ground Reaction Force Component			
Fy1	--- [b]	--- [a,b]	.001	.005	.001 [b]	.001 [b]
Fy2	---	---	.005	.001	---	---
Fy3	---	---	---	--- [c]	---	--- [c]
Fy4	--- [b]	--- [b]	---	---	.001 [b]	.005 [b]
Fy5	---	---	---	.001	---	---

Table 6. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
Medio-lateral Ground Reaction Force Component						
Fx1	---	---[a]	---	---[a]	---	.001
Fx2	---[b]	---[a,b]	---	---[a]	.001[b]	.001[b]
In-shoe Pressure						
P1	---	---	---	---	---	---
P2	---	---	---	---	---	---
P3	---	---	---	.005	---	---
Sagittal Plane Kinematics - Hip Angle						
H1	---[b]	---[b]	---	---	.001[b]	.001[b]
H2	---[b]	---[b]	.001	---[c]	.001[b]	.001[b,c]
H3	---[b]	---[b]	.005	---[c]	.001[b]	.001[b,c]
H4	---[b]	---	---	---	.001[b]	.001
H5	---[b]	---	---	---	.001[b]	---
H6	---	---	---	---	.001[b]	---

Table 6. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Knee Angle			
K1	---	---	.001	---	---	---
K2	---[b]	---[b]	---	---	.005[b]	.001[b]
K3	---[b]	---	.001	.001	.001[b]	---
K4	---[b]	---	---	---	.001[b]	.005
K5	---	---	---	---	---	---
K6	---[b]	---	---	---	.001[b]	.001
			Sagittal Plane Kinematics - Ankle Angle			
A1	---[b]	---[a]	.001	---[a]	.001[b]	---
A2	---[b]	---[b]	.001	.001	.001[b]	.001[b]
A3	---[b]	---	.001[c]	.001	.001[b,c]	---
A4	---[b]	---	---	---	.001[b]	.005
A5	---[b]	---	---	.005	.001[b]	.001
A6	---	---	---	---	---	---

Table 6. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
	Sagittal Plane Kinematics - Metatarsal Angle					
Mt1	---[a,b]	---[a,b]	.001[a]	.001[a]	.001[b]	.001[b]
Mt2	---[b]	---	.005	---	.001[b]	.001[b]
Mt3	---[a,b]	---[a,b]	.001[a]	.001[a]	.001[b]	.005[b]
Mt4	---[b]	---	---	---	.005[b]	.001
	Rearfoot Movement					
Rf1	---	---	---	---	---	---
Rf2	---	---	.005	---	.005	---
Rf3	---	---	---	.005	---	---
Rf4	---	---	---	.005	---	---
Rf5	---	---	---	---	---	---
	EMG - Medial Hamstring					
EMG1	---	---	.005	---	---	---
EMG2	.001	---	---	---	---	---
EMG3	.005[a]	---	---[a]	---	---	---

Table 6. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			EMG - Rectus Femoris			
EMG1	---	---	---	---	---	---
EMG2	---	---	---	---	---	---
EMG3	---	---	---	---	.01	---
			EMG - Anterior Tibialis			
EMG1	---	---	---	---	---	.001
EMG2	---	---	---	---	---	.005
EMG3	---	---	---	---	---	---
			EMG - Gastrocnemius/Soleus			
EMG1	---	.01[a]	---	---[a]	---	---
EMG2	---	---	---	---	---	---
EMG3	---[b]	---	---	---	---[b]	---

Table 6. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Physiological Measures			
M1	.005	---	---	---	.005	.001
M2	---	---	---	---	---	---
M3	---	---	---	---	.005	---

Note. Dashes indicate a nonsignificant main effect.

[a]Significant Fitness x Footwear interaction. [b]Significant Fitness x Load interaction. [c]Significant Footwear x Load interaction.

was significantly affected by footwear. For the men, these were the medio-lateral component of ground reaction force, in-shoe pressure, the activity of the rectus femoris, the anterior tibialis, and the gastrocnemius/soleus muscle groups, and the physiological measures. For the women, none of the parameters associated with the medio-lateral component of the ground reaction force, hip angle, the activity of the muscle groups, or the physiological measures reflected a significant main effect of footwear.

Findings related to the footwear effect are presented in Table 7 for both the men and the women. Instances in which the footwear effect failed to reach significance are indicated. The results of the post-hoc, *HSD* procedure applied to each footwear effect that was significant are also included in the table. In the case of a significant effect, the footwear types with the highest and the lowest means, as determined by the *HSD* procedure, are indicated.

More detailed findings from the analyses of the marching parameters are presented in Appendix D. The odd-numbered tables in that appendix contain the data for the men and the even-numbered contain the data for the women.

Vertical Ground Reaction Force Component (Tables D-1 and D-2)

There were no second-order interactions that were significant on any of the vertical ground force reaction parameters. Furthermore, there were no significant first-order interactions involving footwear.

With regard to footwear main effects, the male data revealed that first maximum force (Fz1), relative time to first maximum force (Fz2), and second maximum force (Fz3) were significantly affected by the type of footwear worn. For first maximum force (Fz1), the lowest mean was obtained with the Rockport hiking boot. This mean differed significantly from the highest means, which were achieved with the combat and the jungle boots. No other differences were significant on this measure. For relative time to first maximum force (Fz2), the fastest time, that for the Nike cross trainer, was significantly different from the two slowest times, those for the Rockport hiking boot and the Red Wing. These were the only significant differences on this parameter. For second maximum force (Fz3), the highest means were achieved with the combat and the jungle boots. These values were significantly different from the values for the remaining footwear items. The lowest mean on this parameter was achieved with the Nike cross trainer. It differed significantly not only from the combat and the jungle boot means, but also from the mean for the Red Wing work boot.

The female data yielded significant effects of footwear on all parameters except total vertical impulse (Fz6). On first maximum force (Fz1), the values for the combat boot, the Nike cross trainer, and the Red Wing were highest. They differed significantly from the lowest values, those for the Reebok Pump and the Rockport hiking boot. There

Table 7. Extreme Values of Footwear Means for Overground and Treadmill Marching Parameters Based on Post Hoc Analyses of Footwear Main Effect

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
	Vertical Ground Reaction Force Component			
Fz1	Roc	Com, Jun	Ree, Roc	Com, Nik, Red
Fz2	Nik	Roc, Red	Ree, Nik	Roc, Red
Fz3	Ree, Nik, Roc	Com, Jun	Ree, Nik	Com, Jun, Red
Fz4	---	---	Com, Jun, Ree, Red	Nik, Roc
Fz5	---	---	Jun, Ree, Roc	Com, Nik, Red
Fz6	---	---	---	---
	Antero-posterior Ground Reaction Force Component			
Fy1[a]	Com, Roc, Red	Jun, Ree, Nik	Jun, Ree	Nik
Fy2	Nik	Com, Jun, Roc, Red	Nik	Red
Fy3	---	---	---	---
Fy4	---	---	---	---
Fy5	---	---	Com	Nik
	Medio-lateral Ground Reaction Force Component			
Fx1	---	---	---	---
Fx2	---	---	---	---
	In-shoe Pressure			
P1	---	---	---	---
P2	---	---	---	---
P3	---	---	Com, Jun, Ree, Roc, Red	Nik

Table 7. Continued

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
	Sagittal Plane Kinematics - Hip Angle			
H1	---	---	---	---
H2	Nik, Roc	Com, Jun, Ree, Red	---	---
H3	Red	Com, Jun, Ree, Nik, Roc	---	---
H4	---	---	---	---
H5	---	---	---	---
H6	---	---	---	---
	Sagittal Plane Kinematics - Knee Angle			
K1	Nik, Roc	Com, Jun	---	---
K2	---	---	---	---
K3	Nik	Com, Jun	Ree, Nik, Roc	Com, Jun, Red
K4	---	---	---	---
K5	---	---	---	
K6	---	---	---	---
	Sagittal Plane Kinematics - Ankle Angle			
A1	Ree	Jun, Nik, Red	---	---
A2[a]	Red	Ree	Com, Jun, Nik, Roc, Red	Ree
A3	Com, Red	Nik, Roc	Com, Jun	Nik, Roc
A4	---	---	---	---
A5[a]	---	---	Ree, Nik, Roc	Com, Jun, Red
A6	---	---	---	---

Table 7. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
Sagittal Plane Kinematics - Metatarsal Angle				
Mt1	Ree, Nik, Roc	Com, Jun	Ree, Nik	Jun, Red
Mt2	Com, Ree, Nik, Roc	Jun	---	---
Mt3	Roc, Red	Com, Jun, Ree	Roc, Red	Jun
Mt4	---	---	---	---
Rearfoot Movement				
Rf1	---	---	---	---
Rf2[a]	Nik, Red	Roc	---	---
Rf3	---	---	Nik, Roc	Ree
Rf4	---	---	Red	Nik, Roc
Rf5	---	---	---	---
EMG - Medial Hamstring				
EMG1[a]	Jun, Nik, Roc	Com, Ree, Red	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
EMG - Rectus Femoris				
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---

Table 7. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		EMG - Anterior Tibialis		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
		EMG - Gastrocnemius/Soleus		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
		Physiological Measures		
M1	---	---	---	---
M2	---	---	---	---
M3	---	---	---	---

Note. Dashes indicate a significance level of $p > .05$. Com = combat boot; Jun = jungle boot; Ree = Reebok Pump; Nik = Nike cross trainer; Roc = Rockport hiking boot; Red = Red Wing work boot.

[a]Values are highest and lowest absolute values.

were no other significant differences on this parameter. The shortest times to first maximum force (Fz2) were associated with the Reebok Pump and the Nike cross trainer. These times differed significantly from the longest times, those for the Rockport hiking boot and the Red Wing. There were no other significant differences among the means. With regard to second maximum force (Fz3), the highest means were associated with the combat boot, the jungle boot, and the Red Wing. These means did not differ from each other, but they were significantly different from the lowest means, those for the Reebok Pump and the Nike cross trainer. There were no other significant findings on this measure. On relative time to second maximum force (Fz4), the times for the Nike cross trainer and the Rockport hiking boot did not differ from each other, but they were significantly longer than those for the other footwear types. There were no additional significant differences on this parameter. With regard to average vertical force (Fz5), the three highest values, which were for the combat boot, the Nike cross trainer, and the Red Wing, did not differ from each other. However, they were significantly greater than the values for the remaining footwear types. There were no further significant findings on this measure.

Antero-posterior Ground Reaction Force Component (Tables D-3 and D-4)

Analyses of the antero-posterior ground reaction force parameters did not yield any significant second-order interactions. In addition, the male data did not reveal any significant first-order interactions involving footwear. However, there were two significant first-order interactions involving footwear in the analyses of the female data. One of these was an interaction between fitness and footwear on maximum braking force (Fy1). The means for the interaction are presented graphically in Figure 20. The interaction appears to be attributable to greater differences among footwear means for the low fitness group than for the other two fitness groups.

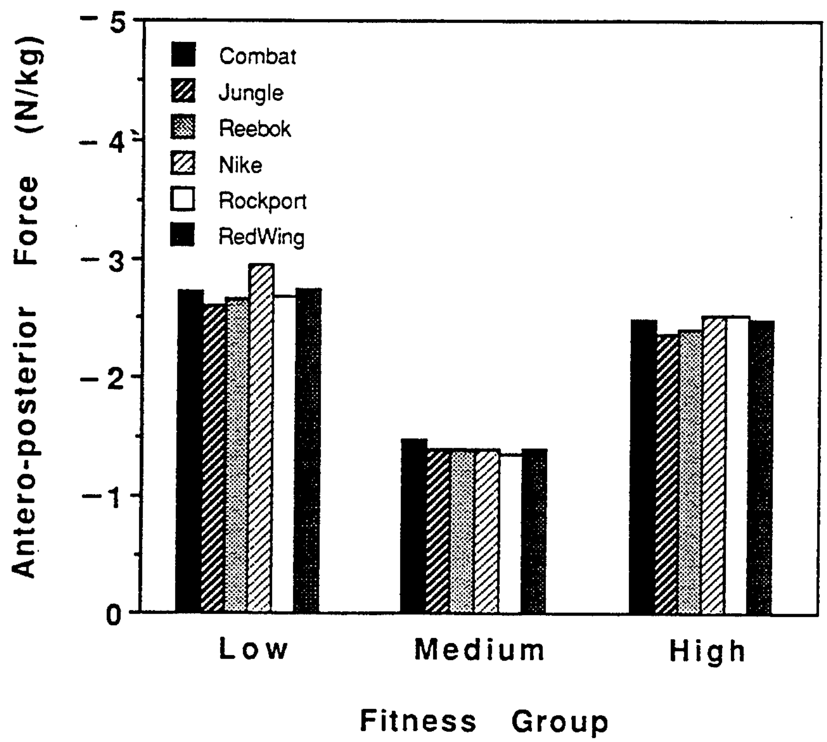

Figure 20. Means on maximum braking force (Fy1), an antero-posterior ground reaction force component, during marching under each footwear condition for women within each fitness group.

The second significant interaction involving footwear in the analyses of the female data occurred in the form of an interaction between footwear and load on relative time to transition force (Fy3). The interaction means are presented graphically in Figure 21. The significant interaction appears to be attributable in part to the relatively low mean for the Rockport hiking boot under the no-load condition and the relatively high mean for this item under the 50-lb load condition. In addition, the jungle boot had a relatively high mean under the no-load condition and a relatively low one under the 50-lb load condition.

In terms of footwear effects, the male data revealed a significant main effect for two parameters. On one of the parameters, maximum braking force (Fy1), the three forces of the largest magnitude were those for the jungle boot, the Reebok Pump, and the Nike cross trainer. These forces did not differ from each other, but they did differ significantly from those for the remaining footwear items. There were no other significant findings on this parameter. Time to maximum braking force (Fy2) was the other parameter significantly affected by footwear in the analyses of the male data. The lowest values, those for the Nike cross trainer, differed significantly from the values for all other footwear types except the Reebok Pump. There were no further significant differences on this measure.

The female data revealed a significant effect of footwear on three parameters. One was maximum braking force (Fy1). The highest magnitude force, which was obtained with the Nike cross trainer, was significantly different from the lowest magnitude forces, which were achieved with the jungle boot and the Reebok Pump. There were no other significant findings on this measure. Another significant parameter in the analyses performed on the female data was relative time to maximum braking force (Fy2). Here, the lowest value, that for the Nike cross trainer, differed significantly from all other values except that for the Reebok Pump. The mean for the Reebok Pump differed significantly only from the highest mean, which was associated with the Red Wing. There were no further significant findings on this measure. Time to maximum propelling force (Fy5) was the other parameter that yielded a significant footwear effect in the analyses of the female data. The highest mean was associated with the Nike cross trainer. It differed significantly from the means for the combat boot, the jungle boot, and the Red Wing. The lowest mean, which was achieved with the combat boot, also differed significantly from the means for the Reebok Pump and the Rockport hiking boot. There were no other significant differences among footwear types on this measure.

Medio-lateral Ground Reaction Force Component (Tables D-5 and D-6)

Neither the male nor the female data yielded a significant main effect of footwear on the medio-lateral ground force reaction parameters. In addition, no second-order interactions were significant. However, there were two instances in which first-order interactions involving footwear were found to be significant. Both resulted from analyses

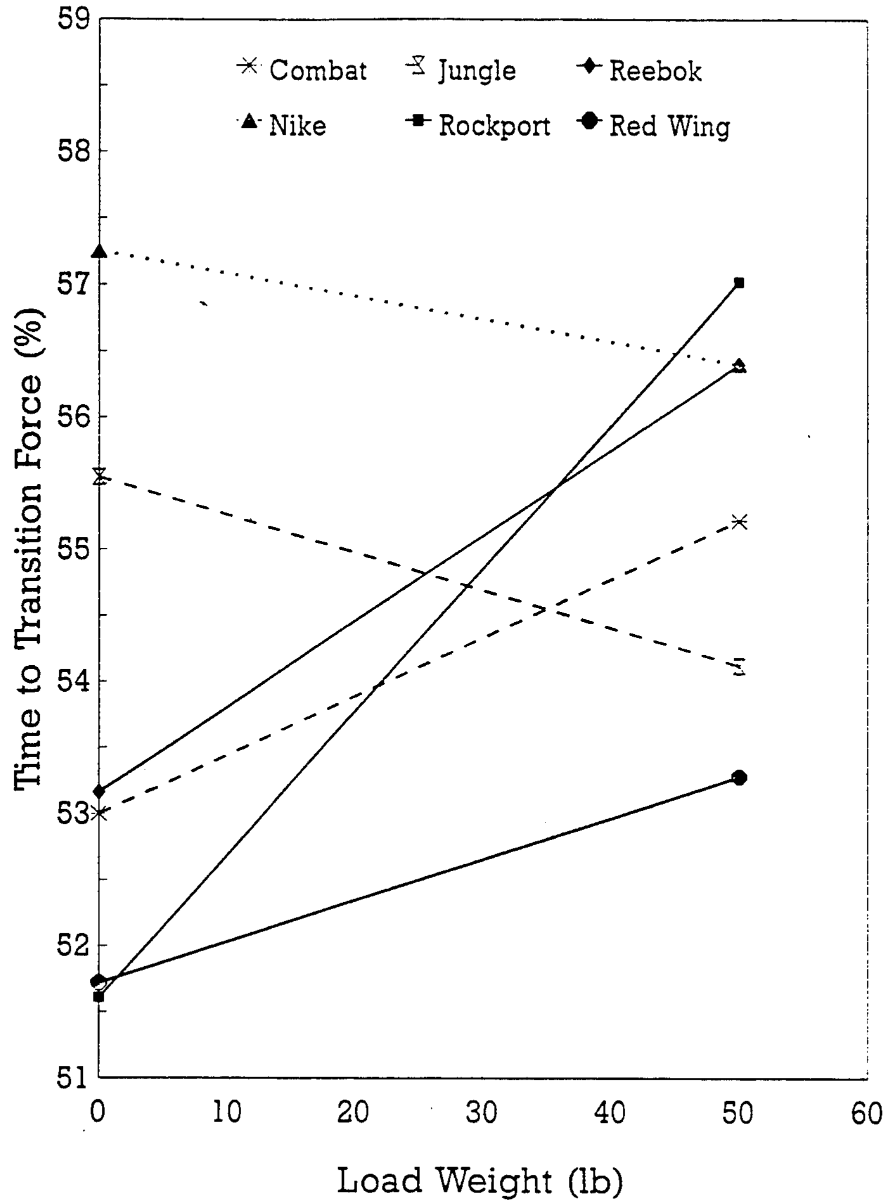

Figure 21. Means for women on relative time to transition force (Fy3), an antero-posterior ground reaction force component, during marching under each footwear and load condition.

of the female data where footwear interacted significantly with fitness on force excursions 0 to 30% of the contact period (Fx1) and over the entire contact period (Fx2).

The interaction means for force excursions 0 to 30% of the contact period are presented graphically in Figure 22 and those for force excursions over the entire contact period are presented in Figure 23. Both interactions appear to be attributable to the relatively greater differences among footwear means in the high fitness group compared with the other two fitness groups.

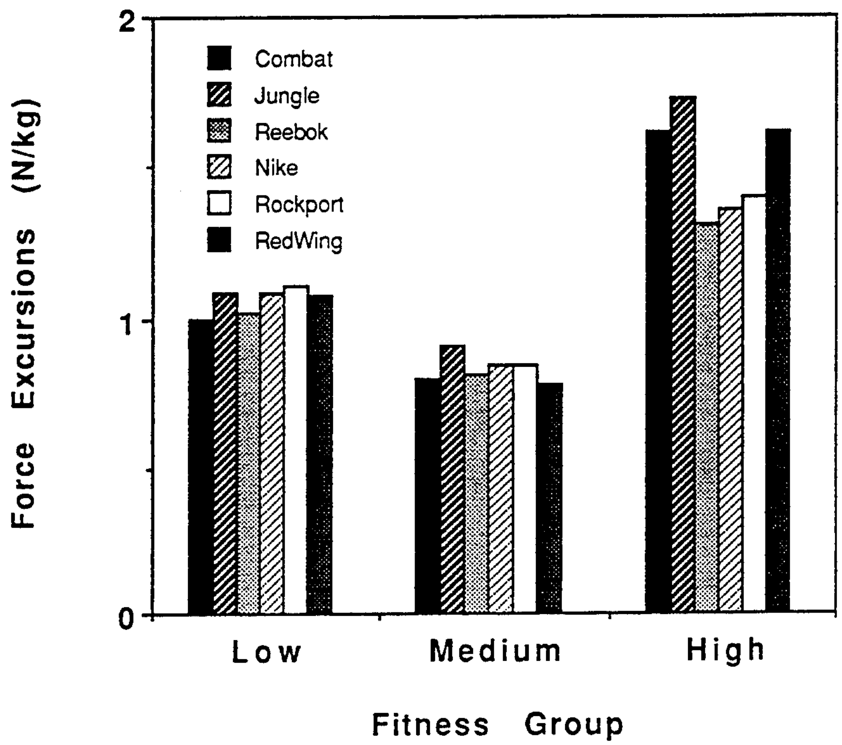

Figure 22. Means on force excursions 0-30% of contact period (Fx1), a medio-lateral ground reaction force component, during marching under each footwear condition for women within each fitness group.

In-shoe Pressure (Tables D-7 and D-8)

There was only one significant finding involving the footwear variable in the analyses of the in-shoe pressure data. The female data revealed a significant main effect of footwear on total movement distance of the COP (P3). Here, the highest mean, which was associated with the Nike cross trainer, differed significantly from the means for the remaining footwear types. No other significant differences were obtained on this parameter.

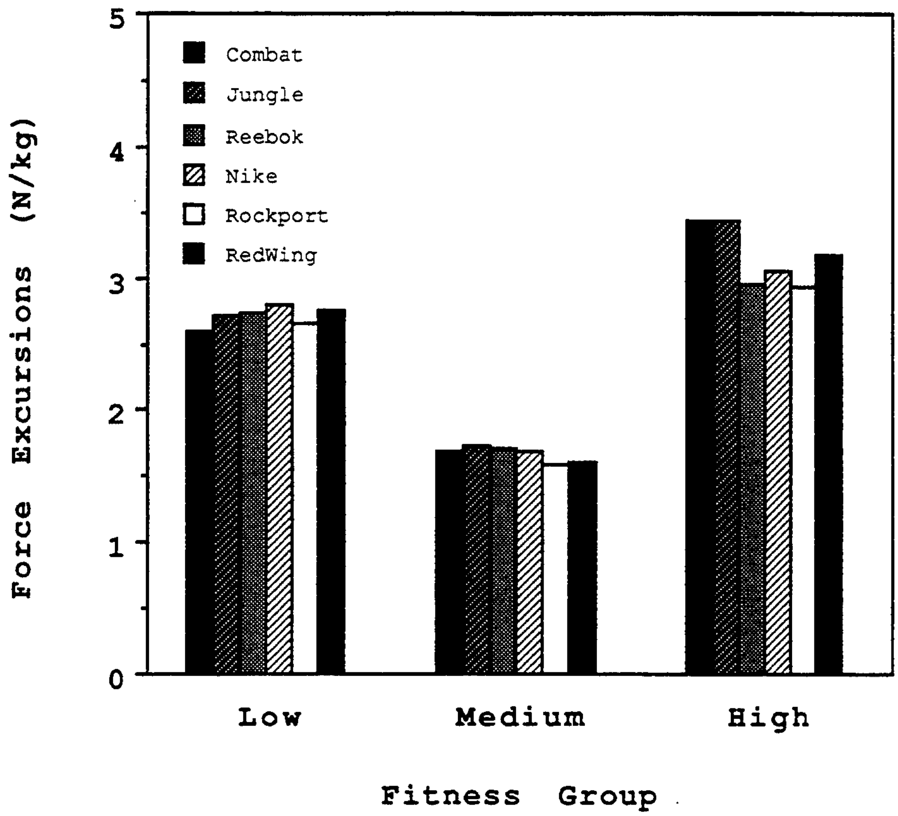

Figure 23. Means for women on force excursions 0-100% of contact period (Fx2), a medio-lateral ground reaction force component, during marching under each footwear condition for women within each fitness group.

Sagittal Plane Kinematics

Hip angle (Tables D-9 and D-10). There were no significant second-order interactions in the analyses of the hip angle data. The male data did not yield any significant first-order interactions involving footwear, but the female data did. These were interactions between footwear and load on the maximum extension (H2) and the maximum flexion velocity (H3) measures. The interaction means for maximum extension are presented in Figure 24 and the means for maximum flexion velocity are in Figure 25. Both interactions appear to be attributable in part to the relatively high values for the Reebok Pump under the no-load condition and the relatively low values under the 50-lb load condition. In addition, the Rockport hiking boot had low values under the no-load and high values under the 50-lb load conditions.

Analyses of the female data did not yield a significant main effect of footwear on any hip angle parameters. In terms of footwear main effects in analyses of the male data,

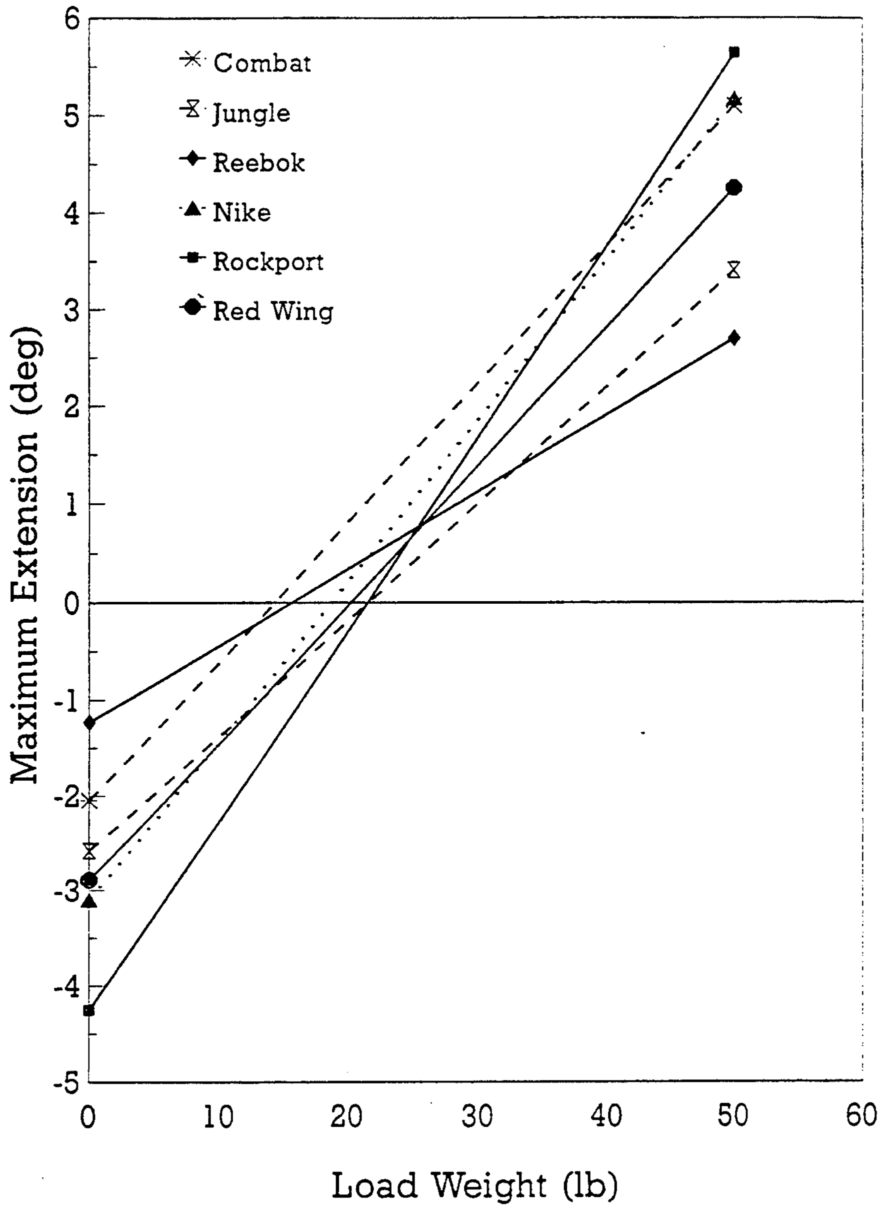

Figure 24. Means for women on maximum hip extension (H2) during marching under each footwear and load condition.

maximum extension (H2) and maximum flexion velocity (H3) were significantly affected by footwear. On the maximum extension measure (H2), the means for the Nike cross trainer and the Rockport hiking boot were significantly lower than the means for all other footwear types. There were no other significant differences among footwear types on this parameter. On maximum flexion velocity (H3), the value for the Red Wing was significantly lower than the values for the other footwear. No other differences were obtained on this parameter.

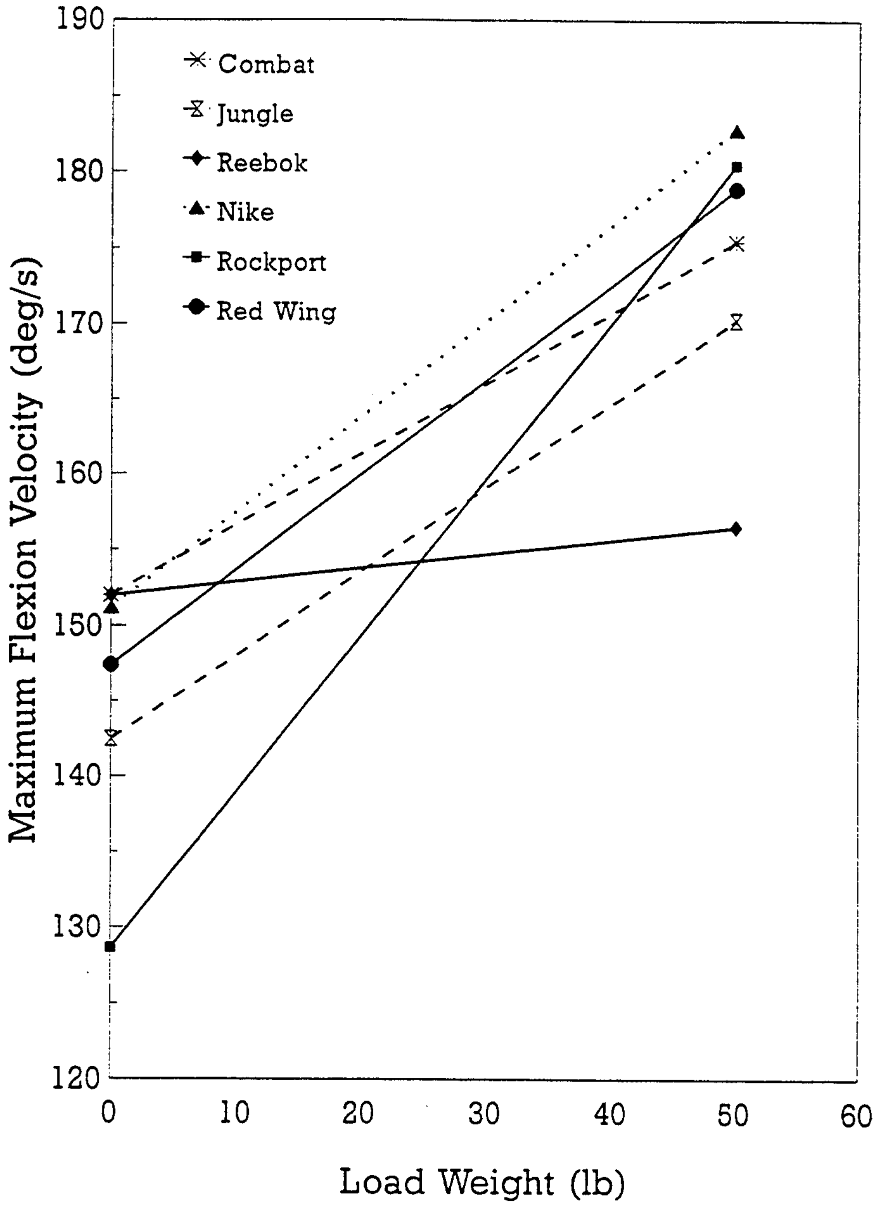

Figure 25. Means for women on maximum hip flexion velocity (H3) during marching under each footwear and load condition.

Knee angle (Tables D-11 and D-12). The second-order interaction was not significant in the analyses of the knee angle data. Furthermore, there were no first-order interactions involving footwear that were significant.

In terms of footwear main effects, the male data yielded significant findings on two parameters. One was maximum flexion (K1). Here, the highest means, those for the combat and the jungle boots, differed significantly from all others except the mean for the Reebok Pump. The lowest means were associated with the Nike cross trainer and the Rockport hiking boot. These means differed from all others except the means for the Red Wing work boot. The Reebok Pump and the Red Wing did not differ from each other. There were no other significant findings on this parameter. The second knee angle parameter significantly affected by footwear in analyses of the male data was maximum flexion velocity (K3). The lowest mean was for the Nike cross trainer. This mean differed significantly from the means for all other footwear types except the Rockport hiking boot. The mean for the Rockport differed significantly from the two highest means, which were associated with the combat and the jungle boots. No other significant differences were obtained on this measure.

Analyses of the female data resulted in a significant footwear effect on one knee angle parameter, maximum flexion velocity (K3). Here, the three highest means did not differ from each other, but did differ from the means for the remaining footwear types. The three highest means were for the combat boot, the jungle boot, and the Red Wing work boot. There were no other significant findings on this measure.

Ankle angle (Tables D-13 and D-14). The second-order interaction did not achieve significance in the analyses of the ankle angle data. However, there was one significant footwear by load interaction. It occurred in the analysis of the male data for maximum plantarflexion velocity (A3). The interaction means are presented graphically in Figure 26. It can be seen that the values for all footwear types except the Reebok Pump increased with increases in load weight. For the Reebok Pump, the mean for the 70-lb load was lower than that for the 50-lb load.

There was also one significant interaction between fitness and footwear. It occurred in the analysis of the female data for maximum plantarflexion (A1). The means for the interaction are presented in Figure 27. It can be seen that the mean for the Reebok Pump was lower than the means for the other footwear types in all three fitness groups. However, the difference between the Reebok mean and the remaining means was greater for the high fitness group than for the other two fitness groups.

In terms of the effects of footwear on ankle angle parameters, analyses of the male data revealed significant findings for maximum plantarflexion (A1), maximum dorsiflexion (A2), and maximum plantarflexion velocity (A3). For the maximum plantarflexion variable (A1), the three highest means were achieved with the jungle boot,

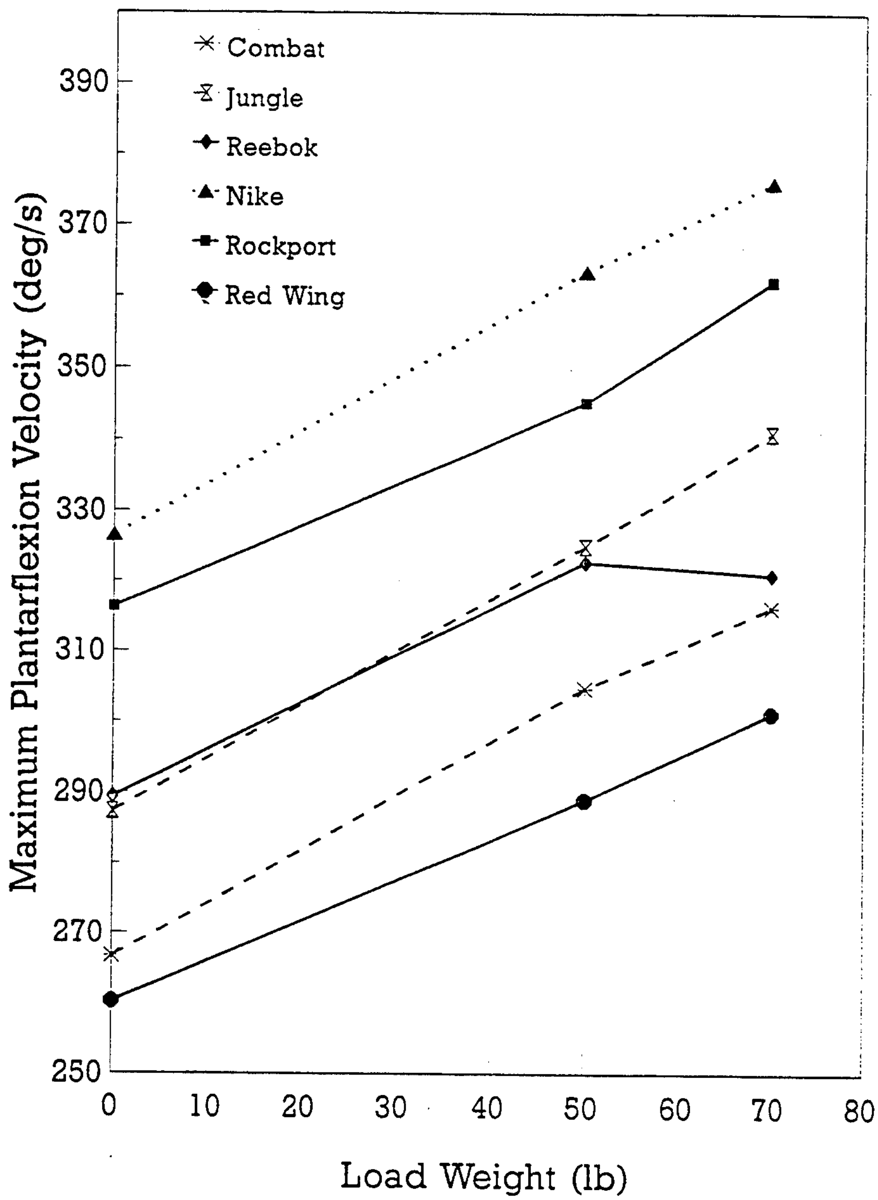

Figure 26. Means for men on maximum ankle plantarflexion velocity (A3) during marching under each footwear and load condition.

the Nike cross trainer, and the Red Wing. These means did not differ from each other, but did differ significantly from the lowest mean, which was achieved with the Reebok Pump. There were no other significant findings for this parameter. For maximum dorsiflexion (A2), a negative quantity, the largest absolute value was for the Reebok

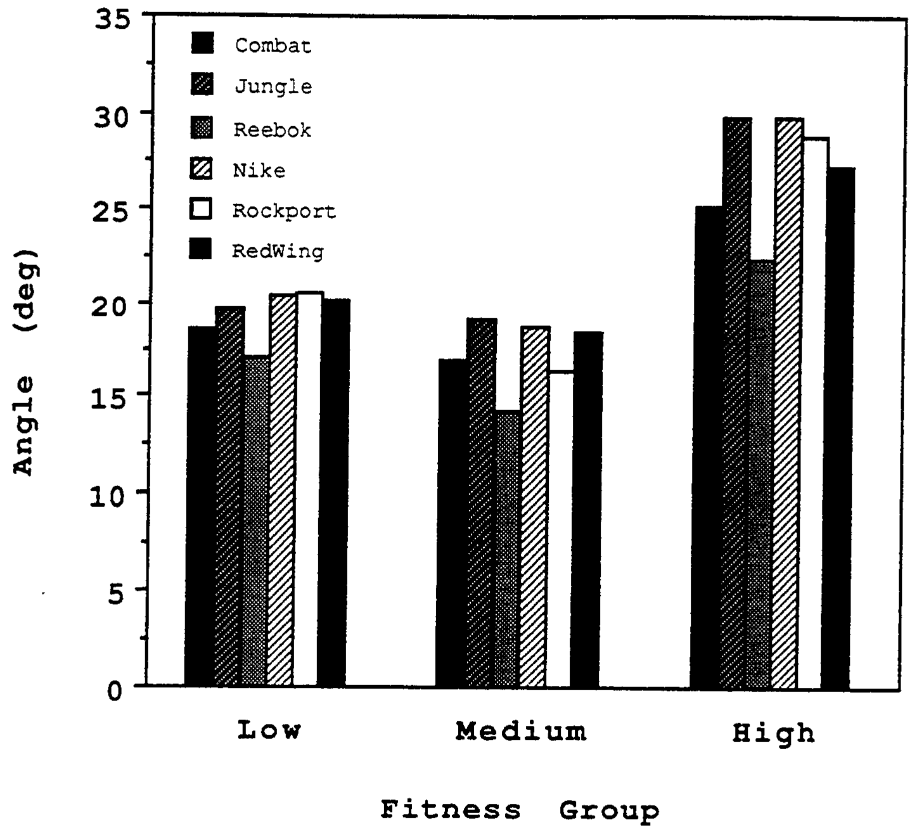

Figure 27. Means on maximum ankle plantarflexion (A1) during marching under each footwear condition for women within each fitness group.

Pump. This value differed significantly from the two lowest absolute values, which were for the jungle boot and the Red Wing. The lower of these two values was for the Red Wing. It differed from the values for all footwear types except the jungle boot. On the maximum plantarflexion velocity measure (A3), the two highest values, those for the Nike cross trainer and the Rockport hiking boot, were not different from each other, but they did differ significantly from the values for the remaining footwear types. The lowest value was achieved with the Red Wing. It differed from all other values except that for the combat boot. There were no other significant differences on this measure.

Analyses of the female data revealed a significant main effect of footwear on maximum dorsiflexion (A2), maximum plantarflexion velocity (A3), and maximum dorsiflexion velocity (A5). For maximum dorsiflexion (A2), a negative quantity, one significant difference was found; the largest absolute value, which was obtained with the Reebok Pump, differed significantly from all other values. On the maximum plantarflexion velocity measure (A3), the largest means, obtained with the Nike cross trainer and the Rockport hiking boot, did not differ from each other, but were significantly different from the remaining means. The smallest mean values, which were associated with the combat and the jungle boots, also did not differ from each other, but they were significantly different from the remaining means. Furthermore, the means intermediate in value, those for the Reebok Pump and the Red Wing work boot, likewise did not differ from each other, but differed significantly from the remaining means. For maximum dorsiflexion velocity (A5), a negative quantity, the highest absolute values were associated with the combat boot, the jungle boot, and the Red Wing. The values for these footwear types did not differ from each other, but were significantly different from the values for the remaining types. No other significant differences were obtained on this parameter.

Metatarsal angle (Tables D-15 and D-16). Neither the male nor the female data revealed a significant second-order interaction on any of the metatarsal angle parameters. However, there were significant first-order interactions involving footwear. These significant findings for both the male and the female data were interactions between fitness and footwear on maximum metatarsal flexion (Mt1) and maximum metatarsal velocity (Mt3). The male means for the significant interactions are presented in Figures 28 and 29; the female means are in Figures 30 and 31.

With regard to the male data for maximum metatarsal flexion in Figure 28, it appears that the significant interaction is attributable to the relatively low value for the Reebok Pump in the low fitness group compared to the value for this footwear in the other fitness groups. In terms of the male data for maximum metatarsal velocity in Figure 29, the significant interaction appears to be due to the fact that, for the low and the high fitness groups, the combat boot had the highest mean and the Red Wing work boot had the lowest, whereas, for the medium fitness group, the jungle boot had the highest value and the value for the Red Wing was approximately equal to the value for the Rockport hiking boot.

The significant interaction between fitness and footwear obtained in analysis of the female data for maximum metatarsal flexion (Figure 30) appears to be attributable to the fact that the Reebok Pump had the lowest mean in both the low and the high fitness groups and the Nike cross trainer had the lowest mean in the medium fitness group. In terms of the significant interaction obtained in analysis of the female data for maximum metatarsal velocity (Figure 31), it appears that the interaction is attributable to the low value for the Reebok Pump in the low and the medium fitness groups and its relatively high value in the high fitness group.

In terms of footwear main effects, all parameters except time to maximum velocity (Mt4) were found to be significant in the analyses of the male data. With regard to maximum flexion (Mt1), the lowest mean was obtained with the Reebok Pump. This mean was significantly different from all others except the means for the Nike cross

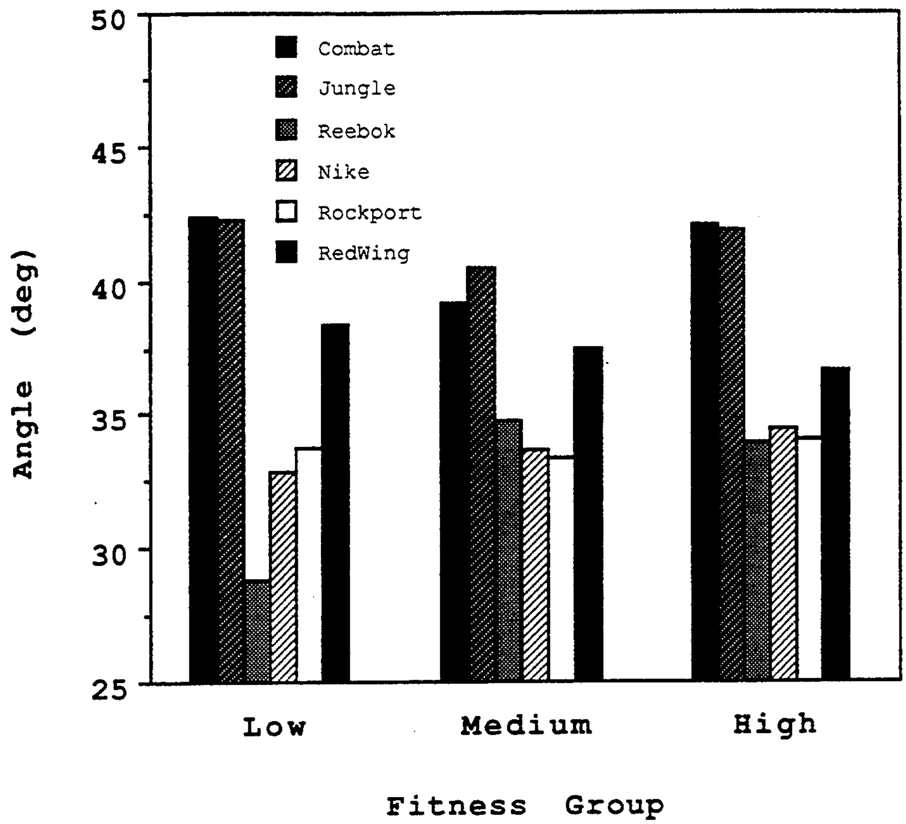

Figure 28. Means on maximum metatarsal flexion (Mt1) during marching under each footwear condition for men within each fitness group.

trainer and the Rockport hiking boot. The means for these two footwear types differed significantly from the means for the combat and the jungle boots. The highest mean was achieved with the jungle boot. The mean for the jungle boot was significantly different from all means, except that for the combat boot. For the time to maximum flexion measure (Mt2), the slowest time was associated with the jungle boot. The mean for the jungle boot differed significantly from the means for all other footwear types except the Red Wing work boot. There were no further significant findings on this measure. On the maximum velocity parameter (Mt3), the values for the combat boot, the jungle boot, and the Reebok Pump did not differ from each other, but they were significantly higher than the values for the remaining footwear types. The values for the Rockport hiking boot and the Red Wing did not differ, but were significantly lower than those for all other footwear types. No other findings on this measure were significant.

The analyses of the female data yielded significant footwear effects on two parameters, maximum flexion (Mt1) and maximum velocity (Mt3). On maximum flexion (Mt1), the means for the Reebok Pump and the Nike cross trainer did not differ from

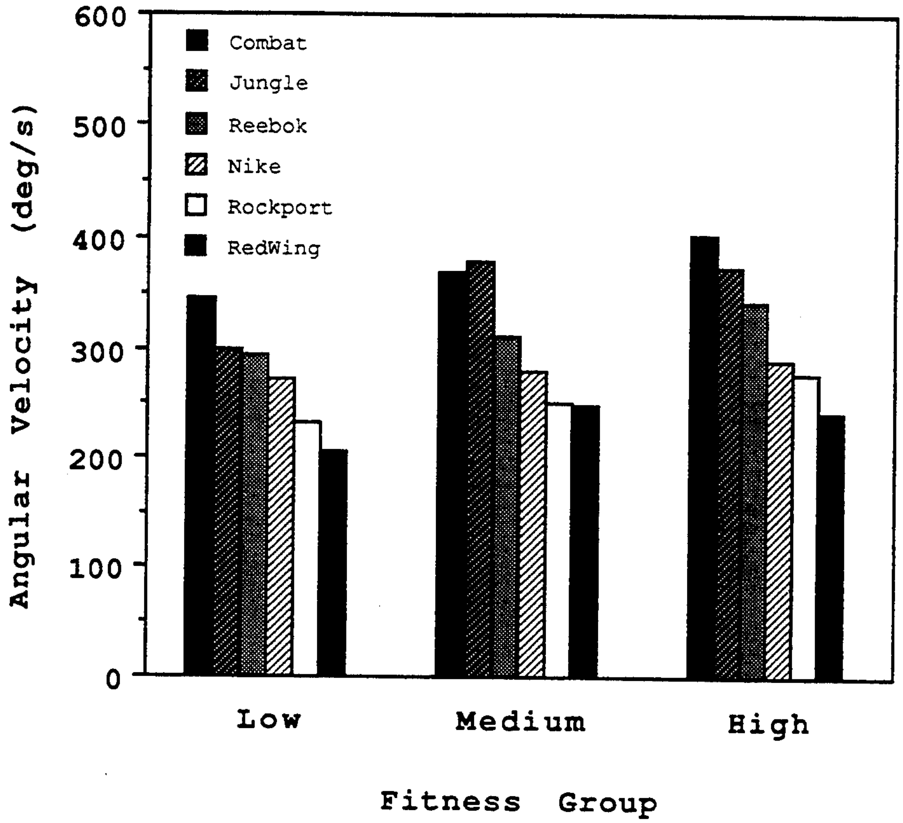

Figure 29. Means on maximum metatarsal flexion velocity (Mt3) during marching under each footwear condition for men within each fitness group.

each other, but they were significantly lower than the means for the remaining footwear conditions. The highest mean was associated with the jungle boot. It differed significantly from the means for all other footwear types except the Red Wing. In addition, the mean for the Red Wing did not differ from the combat boot mean. With regard to maximum velocity (Mt3), the value for the jungle boot was significantly higher than the values for the remaining footwear types, with the exception of the combat boot. The means for the Rockport hiking boot and the Red Wing were significantly lower than all other means except those for the Reebok Pump and the Nike cross trainer. No other differences were significant on this parameter.

Rearfoot Movement (Tables D-17 and D-18)

The analyses of the rearfoot movement parameters did not reveal any second-order interactions that were significant or any significant first-order interactions.

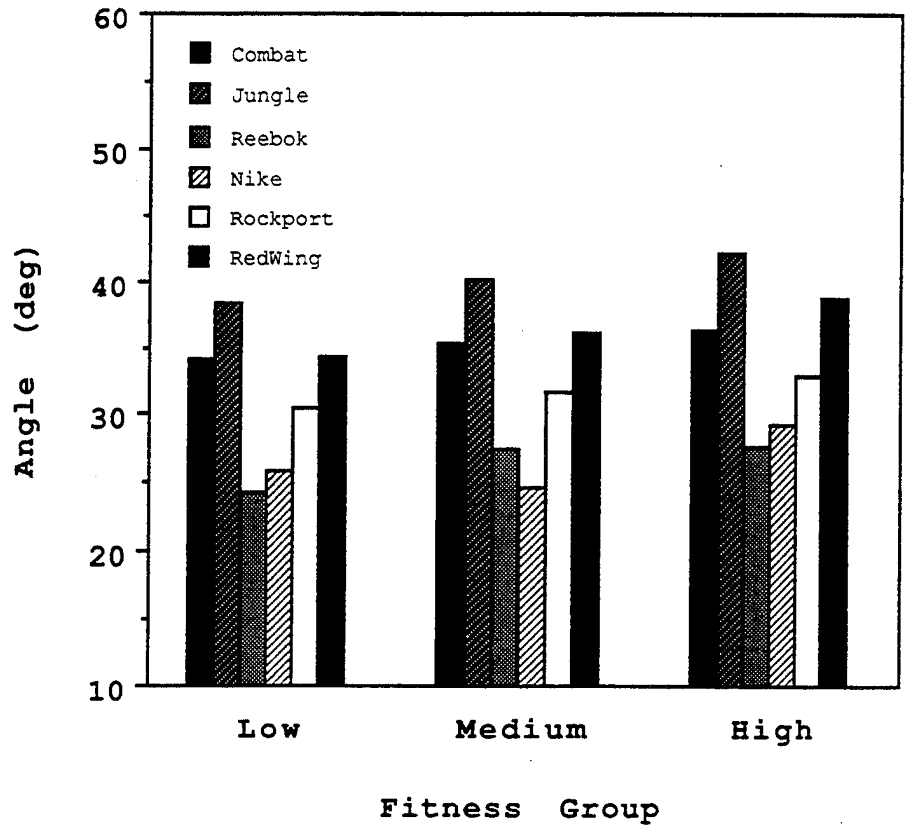

Figure 30. Means on maximum metatarsal flexion (Mt1) during marching under each footwear condition for women within each fitness group.

Analyses of the male data yielded a significant main effect of footwear on one rearfoot movement parameter. This was maximum rearfoot angle (Rf2), a negative quantity. The smallest absolute values were obtained with the Nike cross trainer and the Red Wing. These values were significantly different from the highest absolute value, which was associated with the Rockport hiking boot. There were no other significant differences on this measure.

Analyses of the female data yielded significant effects of footwear on two parameters. One of these was time to maximum rearfoot angle (Rf3). Here, the lowest values were for the Nike cross trainer and the Rockport hiking boot. These values differed significantly from those for the other footwear types. The highest mean, that for the Reebok Pump, differed significantly from all other means except that for the Red Wing. There were no further significant findings on this measure. The other significant footwear effect occurred on total rearfoot motion (Rf4). Here, the highest means were

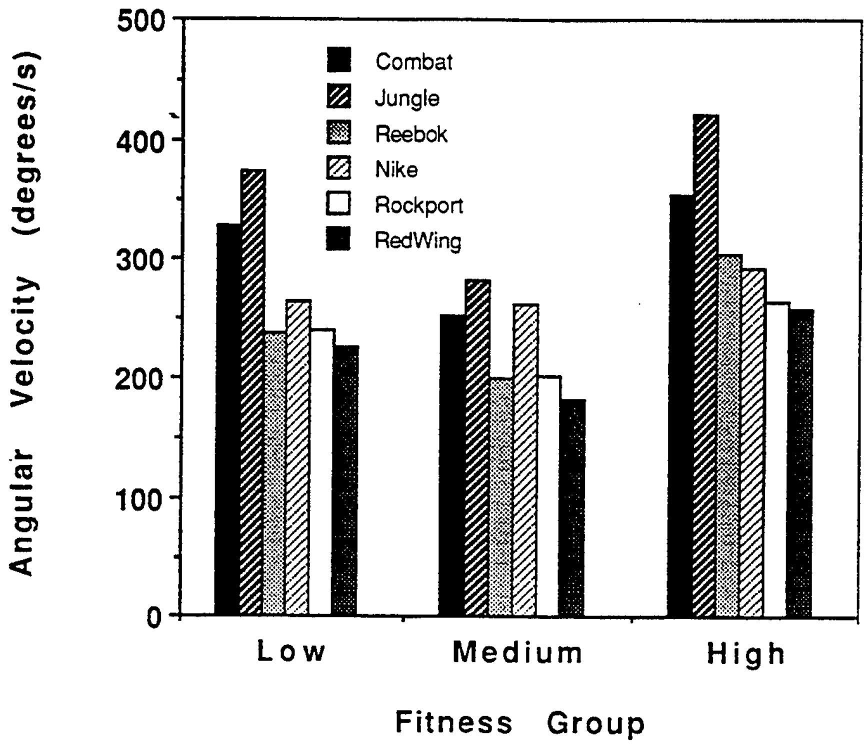

Figure 31. Means on maximum metatarsal flexion velocity (Mt3) during marching under each footwear condition for women within each fitness group.

achieved with the Nike cross trainer and the Rockport hiking boot. These means differed from the lowest, which was achieved with the Red Wing. No other significant differences were obtained on this measure.

EMG

Medial hamstring (Tables D-19 and D-20). Analyses of the medial hamstring measures yielded one significant interaction involving footwear. This was a first-order interaction between fitness and footwear in the analysis of the male data for area under the curve (EMG3). The means for the interaction are presented in Figure 32. The interaction appears to be attributable to the differing relationship across fitness groups of the values for the Nike cross trainer and the Rockport hiking boot relative to the values for the other footwear types. The means for the Nike cross trainer and the Rockport hiking boot were, depending upon the fitness group, higher than, lower than, or intermediate to the other footwear means.

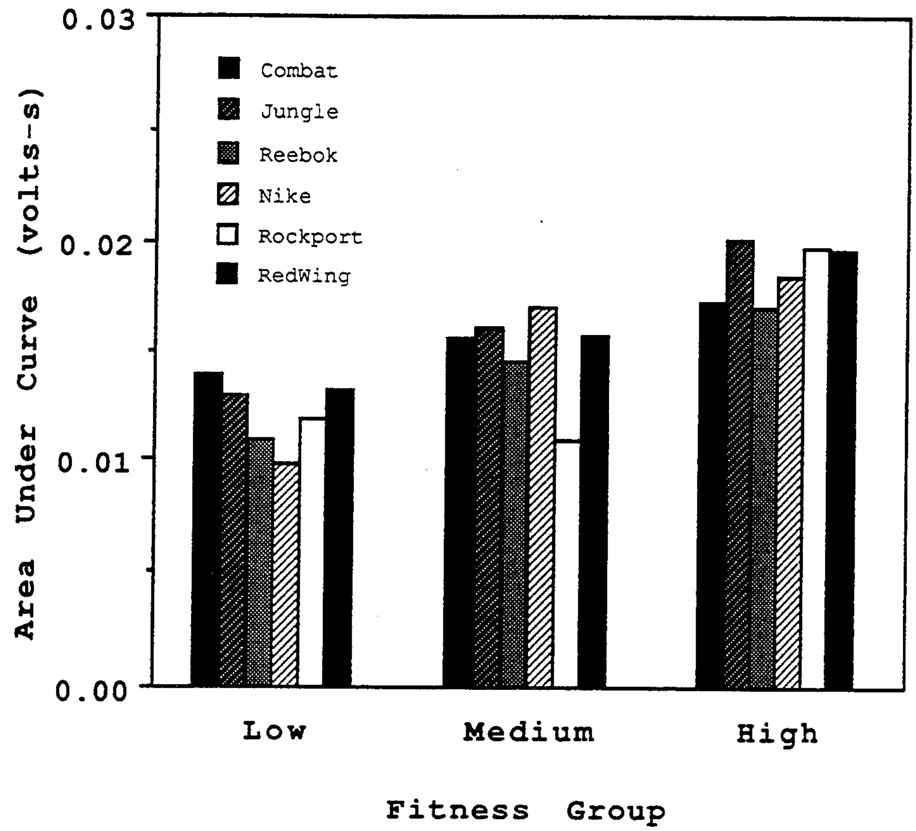

Figure 32. Means on area under the curve (EMG3) for the medial hamstrings during marching under each footwear condition for men within each fitness group.

With regard to significant main effects of footwear, the male data revealed a significant footwear effect on time to onset of muscle activity (EMG1), a negative quantity. The three highest absolute values did not differ from each other, but they did differ from the three lowest absolute values, which in turn did not differ from each other. The three highest values were for the combat boot, the Reebok Pump, and the Red Wing work boot. The female data did not yield any significant main effects of footwear.

Rectus femoris (Tables D-21 and D-22). Analyses of rectus femoris measures did not yield any significant interactions or significant main effects of footwear.

Anterior tibialis (Tables D-23 and D-24). Analyses of the anterior tibialis measures did not yield any significant interactions or significant main effects of footwear.

Gastrocnemius/soleus (Tables D-25 and D-26). Analyses of these parameters yielded only one significant finding involving footwear. It was an interaction between fitness and footwear on time to onset of muscle activity (EMG1) in analysis of the female data. The means for the interaction are presented graphically in Figure 33. It can be seen that the means for the medium fitness group are negative, whereas those for the other two fitness groups are positive, reflecting the significant fitness main effect. The interaction between fitness and footwear appears to be attributable to the relatively high absolute value for the Red Wing work boot in the medium and high fitness groups and the relatively low value for this footwear in the low fitness group. Also, the absolute value for the Nike cross trainer is low in the medium fitness group compared with its value in the other two fitness groups.

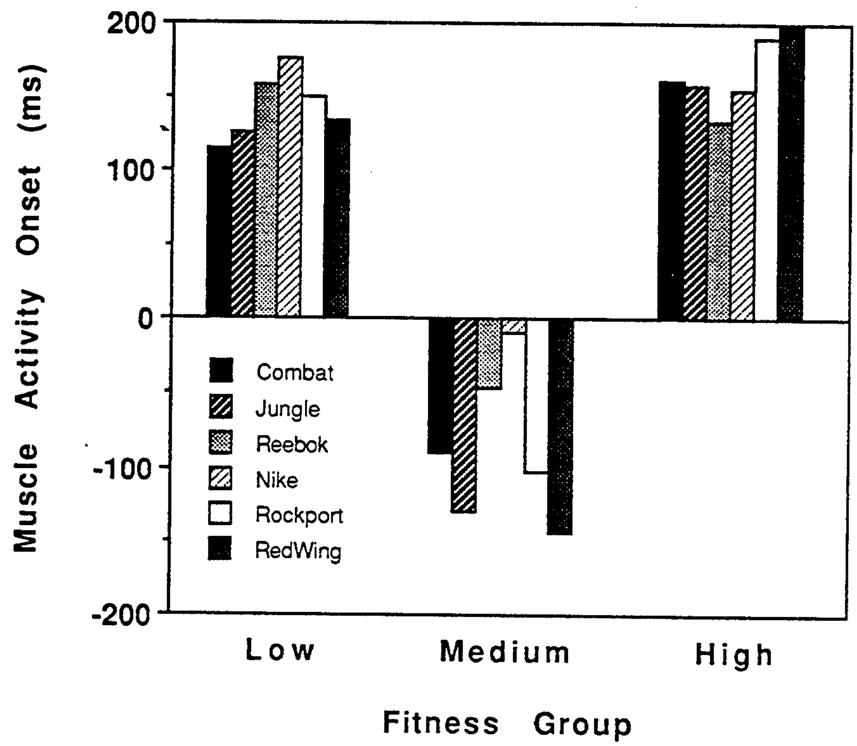

Figure 33. Means on time to onset of activity (EMG1) of the gastrocnemius/soleus muscle group during marching under each footwear condition for women within each fitness group.

Physiological Measures (Tables D-27 and D-28)

No significant effects involving footwear were obtained in the analyses of the physiological measures.

Discussion

Findings from the analyses of the male and the female data for first maximum vertical force during overground marching were similar to the findings on this measure during overground walking to the extent that the values for the military boots did not differ significantly from those for the Nike cross trainer, although a difference would be expected on the basis of the peak g values obtained in the materials testing phase (Hamill and Bensel, 1992). However, the data collected during walking revealed that the first maximum vertical force for the Red Wing work boot was significantly higher than the values for the military boots and the Nike cross trainer. During overground marching, on the other hand, the first maximum force values for these four footwear types did not differ significantly. Furthermore, for the men, the vertical forces of the largest magnitude during marching were associated with the jungle boot followed by the combat boot and, for the women, the highest magnitude forces were associated with the Red Wing work boot, followed by the combat boot.

In the analyses of the vertical ground reaction forces during overground walking, it was found that the second maximum force parameter, the thrust or propulsive peak, differentiated the military boots from the Nike cross trainer in the direction expected based upon the impact test data collected during the materials testing phase (Hamill and Bensel, 1992). That is, the military boots were associated with relatively large amplitude forces and the Nike cross trainer with relatively small. The findings during overground marching were similar to those for overground walking. For the men, the second vertical forces of the highest magnitude were associated with the combat and the jungle boots and the force of the lowest magnitude was associated with the Nike cross trainer, along with the Reebok Pump and the Rockport hiking boot. For the women, the highest values of second maximum vertical force were for the military boots and the Red Wing work boot. These values, which did not differ significantly from each other, were significantly different from the two lowest values, which were for the Nike cross trainer and the Reebok Pump.

Unlike the findings for overground walking, the data for overground marching did not reveal significant differences between the military boots and the Nike cross trainer on the total vertical force impulse measure. Indeed, neither the male nor the female data yielded a significant footwear effect on this parameter.

As was the case for overground walking, the results for overground marching reflected to only a limited extent the finding from the materials testing phase that the shortest times to peak g were associated with the military boots. For both the men and the women, the shortest times to first maximum force during overground marching occurred not with the military boots, but with the Nike cross trainer. The values for the military boots did not differ significantly from the values for the cross trainer or from the values for any of the other footwear items. With regard to time to second maximum force, the male data did not reveal a significant footwear effect. However, the female data did, and the shortest times to second maximum force were associated with the military boots. These values differed significantly from the two highest values, which were for the Nike cross trainer and the Rockport hiking boot.

Again, as was found for overground walking, the analyses of in-shoe measurements of peak heel and peak forefoot pressures did not yield a significant footwear effect. Thus, neither overground walking nor marching provided evidence to support the materials test finding of higher peak pressures for the military boots than for the commercial footwear.

As they pertain to peak pressure at the foot/shoe interface, the results for marching, like those for walking, revealed the performance of the military boots to be better than expected on the basis of the materials testing insofar as the military boots yielded values comparable to those of the other footwear items, including the Nike cross trainer. However, for marching as for walking, the military boots were associated with relatively large magnitudes of vertical force during ground contact, particularly when contrasted with the Nike cross trainer and the Reebok Pump.

The findings for overground marching, like those for overground walking, support the impact results from the materials testing (Hamill and Bensel, 1992) in terms of the magnitudes of vertical forces being greater with the military boots than with some of the commercial items, particularly the Nike cross trainer. On the other hand, the overground marching data did not reflect the materials test finding with regard to forefoot flexibility of the footwear items. On the flexibility test, the combat and the jungle boots and the Red Wing work boot were found to be the stiffest of the footwear types tested (Hamill and Bensel, 1992). During locomotion, the footwear items would be expected to be associated with higher levels of muscle activity than the other items because of greater muscular effort required to bend the foot and the shoe. However, for overground marching, as was the case for overground walking, footwear did not have a significant effect on the amplitude of the signal from any of the four muscle groups recorded in the study. The metatarsal joint angle data indicated that wearers bent the military boots and the Red Wing work boot during overground marching to a greater extent than they did the other footwear. This finding, which was also obtained during overground walking, was revealed on the maximum metatarsal flexion parameter.

On the metatarsal flexion measure for marching, the largest angles were associated with the military boots and the Red Wing work boot. This was the case for both the male and the female data sets. Both the male and the female data sets also yielded a significant interaction between fitness and footwear. However, for both genders and for all fitness groups, the largest angles were associated with the military boots and the Red Wing work boot.

Again as was found for overground walking, the maximum metatarsal flexion velocities for marching were relatively high when the military boots were used. Thus, during both walking and marching with the military boots, metatarsal flexion described a relatively large angular excursion and involved a high velocity movement.

With regard to rearfoot movement, the overground walking data provided only limited evidence to support the finding from the materials testing that the military boots and the Red Wing work boot are highly stable compared with the other footwear studied (Hamill and Bensel, 1992). Likewise, the marching data reflected the materials test finding to only a limited extent. Footwear had a significant effect on total rearfoot motion during marching in the analysis of the female data, but not the male data. For the female data, the smallest angular excursions occurred with the Red Wing work boot, followed by the military boots, and the largest excursions occurred with the Nike cross trainer and the Rockport hiking boot. Although the values for the military boots were relatively low, as would be expected from the materials testing results, they did not differ significantly from those for any of the other footwear types. On the maximum rearfoot angle parameter, the male data for marching yielded a significant footwear effect, but the female data did not. The findings for the men are not in the expected direction insofar as the angular excursions with the military boots were among the highest and the lowest was for the Nike cross trainer.

During walking, it was found that footwear had a significant effect on several of the antero-posterior ground reaction force variables. This was also the case during marching. The male data for maximum braking force again yielded a significant footwear effect. The combat boot, along with the Rockport hiking boot and the Red Wing work boot, was associated with relatively low amplitude forces. The values for these three footwear types did not differ from each other, but they did differ from the values for the remaining footwear items. Thus, the two military boots differed with relatively low braking forces being found for the combat boot and relatively high forces for the jungle boot. In the analysis of the female data for maximum braking force, a significant interaction between footwear and fitness group was obtained. However, regardless of fitness group, the forces associated with the combat boot and the Nike cross trainer were relatively high and the forces associated with the jungle boot and the Reebok Pump were relatively low. Thus, there was an inconsistency between the male and the female data with regard to the relative standing of the military boots.

As was the case for walking, time to maximum braking force during marching was significantly affected by the footwear worn. For both the men and the women, the shortest times were associated with the Nike cross trainer, followed by the Reebok Pump. The times for the military boots did not differ significantly from the longest times, which were for the Red Wing work boot.

During marching, as during walking, maximum propelling force was not affected by the footwear worn. However, analysis of the female data, but not the male, did reveal a significant effect of footwear on relative time to maximum propelling force. The results were similar to those obtained during walking. Again, the longest times were associated with the Nike cross trainer and the Rockport hiking boot. The shortest times were achieved with the combat boot, followed by the jungle boot.

The findings for amplitude and time of maximum braking force during marching reflect well on the military boots, as was also the case during walking. Compared with the Nike cross trainer, the amplitudes of maximum braking force during marching were lower with the military boots and the maximum forces occurred later in the ground contact period. However, at least in the case of the women, the propelling forces occurred earlier in the ground contact period with the military boots than with the Nike cross trainer.

In examining the knee angle variables derived from the sagittal plane kinematics during walking, it was found that knee flexion angles were large and maximum knee flexion velocities were high when the military boots or the Red Wing work boots were used, compared with the other footwear tested. The findings on these parameters were similar for marching. With regard to maximum knee flexion during marching, the two highest values in the male data set were for the combat and the jungle boots. These values differed significantly from the two lowest, which were for the Nike cross trainer and the Rockport hiking boot. Although there was not a significant footwear effect in the analysis of the female data for maximum knee flexion angle during marching, the data for both the men and the women on the maximum knee flexion velocity parameter indicated a significant effect. The highest velocities were associated with the military boots, followed by the Red Wing work boot.

From the ankle angle data recorded during walking, it was found that maximum plantarflexion did not vary directly with the height of the footwear upper. This was also found in the ankle angle data recorded during marching. The male data for marching yielded a significant footwear effect on maximum plantarflexion angle; the lowest value occurred with the Reebok Pump and the highest with the jungle boot, followed by the Nike cross trainer and the Red Wing work boot. The female data yielded a significant interaction between footwear and fitness group on the maximum plantarflexion angle measure. However, for every fitness group, the Reebok Pump had the lowest maximum plantarflexion values. The highest values varied across fitness groups. The low fitness group evidenced the largest angular excursions with the Rockport hiking boot. The highest value for the medium fitness group was associated with the jungle boot. In the high fitness group, the values for the jungle boot and the Nike cross trainer were equal and higher than all other values.

During walking, maximum plantarflexion velocity varied with upper height in a more ordered fashion than maximum plantarflexion angle and velocity was found to increase with decreases in the height of the upper. Maximum plantarflexion velocity during marching did not vary directly with upper height. However, both the male and the female data revealed that the lowest velocities were associated with the military boots and the Red Wing work boot and the highest with the Nike cross trainer and the Rockport hiking boot.

Maximum dorsiflexion angle during marching was significantly affected by footwear in the analyses of both the male and the female data and, as was found on this measure during walking, the extent of angular excursion did not vary directly with the height of the footwear upper. In both the male and the female data sets for marching, the smallest maximum dorsiflexion angle occurred with the Red Wing work boot and the largest with the Reebok Pump. However, the three smallest maximum angles were associated with the three footwear types with the highest uppers and the three largest angles were associated with the three footwear types with the lowest uppers. This is the same relationship among footwear types that was obtained during walking and again provides some evidence that height of the upper affected the extent of dorsiflexion.

Analysis of the male data for maximum dorsiflexion velocity during marching did not yield a significant footwear effect, but analysis of the female data did. Velocity did not vary in an ordered fashion with upper height. However, as was also the case during walking, the greatest negative magnitudes of joint angular velocities were associated with the military boots and the Red Wing work boot, the footwear with the highest uppers.

With regard to another physical characteristic of footwear, its mass, the data for oxygen consumption and heart rate measured during marching did not reflect a difference in energy cost of locomotion as a function of differences in footwear mass. Thus, as was the case during walking, the measures of energy cost did not differentiate between the military boots and the other footwear types. However, the combat and the jungle boots did differ from the Nike cross trainer and other footwear on a number of the parameters recorded during marching.

Considering the overall findings for marching, it appears, as it did for walking, that the combat and the jungle boots did not absorb vertical ground reaction forces as effectively as some of the other footwear tested did. The antero-posterior ground reaction force variables indicated that braking forces during marching were of a lower magnitude and occurred later in the ground contact period with the military boots. Furthermore, the military boots were associated during both walking and marching with extensive flexion at the knee that occurred at a relatively high velocity. Data for the metatarsal joint indicated greater angular excursions about the joint with the military boots and the velocity of the movement was relatively high, as was also the case during walking. Ankle dorsiflexion was limited during marching with the military boots, as it was during walking, and was associated with relatively large negative magnitudes of angular velocity. In addition, there was some evidence, mainly in the women's performance during marching, that there was less movement of the calcaneus relative to the lower leg when the military boots were used compared with some of the other footwear types.

Overground and Treadmill Running (3.40 m/s)

Results

Summary

Interactions found to be significant in the analyses of the male and the female data for running are indicated in Table 8. As was the case for walking and marching, the analyses of the parameters for running did not yield any significant second-order interactions. However, significant first-order interactions involving footwear were again obtained. There was one significant interaction between footwear and load. This was found in the analysis of the female data for RER (M2). Significant interactions between fitness and footwear occurred in both the male and the female analyses. For the male data, a significant interaction between fitness and footwear occurred on medio-lateral force excursions 0 to 30% of the contact period (Fx1), maximum dorsiflexion at the ankle (A2), and maximum metatarsal flexion (Mt1). For the female data, the interaction between fitness and footwear was also significant on these parameters (Fx1, A2, and Mt1). In addition, the interaction was significant in analyses of other parameters for the female data. These were maximum antero-posterior braking force (Fy1), maximum antero-posterior propelling force (Fy4), medio-lateral force excursions over the entire contact phase (Fx2), and time to beginning of activity of the gastrocnemius/soleus muscle group (EMG1).

A summary of the significance levels of the main effects for each of the parameters measured during running is presented in Table 8. As indicated in the table, footwear had a significant main effect on a number of the parameters. However, there were again categories of measures in which none of the parameters was significantly affected by footwear. For the men, these were in-shoe pressure, kinematics related to hip angle, activity of the medial hamstring, the rectus femoris, and the gastrocnemius/soleus muscle groups, and the physiological measures. For the women, footwear did not have a significant main effect on the parameters associated with antero-posterior ground reaction forces, kinematics related to hip and knee angles, and the activity of the four muscle groups.

Table 8. Significance of Main Effects and Summary of Significant Interactions in the Analyses of Overground and Treadmill Running Parameters

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Vertical Ground Reaction Force Component			
Fz1	---	---	.005	---	---	---
Fz2	---	---	.001	.001	.001	.005
Fz3	---[b]	---[b]	---	---	.001[b]	.001[b]
Fz4	---	---[b]	---	.001	---	.005[b]
Fz5	---[b]	---[b]	---	---	.001[b]	.001[b]
Fz6	---[b]	---[b]	---	---	.001[b]	.001[b]
			Antero-posterior Ground Reaction Force Component			
Fy1	---	---[a,b]	---	---[a]	---	.001[b]
Fy2	---	---	.005	---	---	---
Fy3	---	---	---	---	---	---
Fy4	---	---[a,b]	---	---[a]	.001	.001[b]
Fy5	---	---	---	---	---	---

Table 8. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
Medio-lateral Ground Reaction Force Component						
Fx1	---[a]	---[a]	.001[a]	.001[a]	---	---
Fx2	---	---[a]	.001	.001[a]	---	---
In-shoe Pressure						
P1	---	---	---	.005	---	.005
P2	---	---	---	---	---	---
P3	---	---	---	.005	---	---
Sagittal Plane Kinematics - Hip Angle						
H1	---[b]	---[b]	---	---	.001[b]	---[b]
H2	---[b]	---	---	---	.001[b]	---
H3	---	---	---	---	---	---
H4	---	---	---	---	.001	---
H5	---[b]	---	---	---	.001[b]	---
H6	---	---	---	---	---	---

Table 8. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Knee Angle			
K1	---	---	---	---	.005	---
K2	--- [b]	---	---	---	.001[b]	.005
K3	--- [b]	---	.001	---	.001[b]	.005
K4	--- [b]	---	---	---	.005[b]	---
K5	---	---	---	---	---	---
K6	---	---	---	---	---	.001
			Sagittal Plane Kinematics - Ankle Angle			
A1	--- [b]	--- [b]	.001	.001	.001[b]	.001[b]
A2	--- [a]	--- [a]	.001[a]	.001[a]	---	---
A3	--- [b]	---	.001	.001	.001[b]	---
A4	--- [b]	---	.005	.001	.001[b]	.001
A5	--- [b]	---	.001	.001	.001[b]	.005
A6	--- [b]	--- [b]	---	---	.001[b]	.001[b]

Table 8. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Metatarsal Angle			
Mt1	---[a,b]	---[a,b]	.001[a]	.001[a]	.001[b]	.001[b]
Mt2	---[b]	---[b]	---	---	.001[b]	.001[b]
Mt3	---[b]	---	.001	---	.001[b]	---
Mt4	---[b]	---[b]	---	---	.001[b]	.001[a]
			Rearfoot Movement			
Rf1	---[b]	---	.001	.01	.005[b]	---
Rf2	---[b]	---[b]	---	.005	.001[b]	.005[b]
Rf3	---[b]	---	---	---	.001[b]	.005
Rf4	---	---	.01	.001	---	---
Rf5	---	---	---	.005	.001	---
			EMG - Medial Hamstring			
EMG1	---	---	---	---	---	---
EMG2	---	---	---	---	---	.005
EMG3	---	---	---	---	---	.01

Table 8. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			EMG - Rectus Femoris			
EMG1	---	---	---	---	---	---
EMG2	---[b]	---[b]	---	---	.005[b]	.001[b]
EMG3	---	---	---	---	.01	.001
			EMG - Anterior Tibialis			
EMG1	---	---[b]	---	---	.005	.001[b]
EMG2	---	---	---	---	.005	---
EMG3	---	---	.001	---	---	.001
			EMG - Gastrocnemius/Soleus			
EMG1	---	---[a]	---	---[a]	---	---
EMG2	---[b]	---[b]	---	---	.001[b]	.001[b]
EMG3	---[b]	---	---	---	---	---

Table 8. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Physiological Measures			
M1	---[b]	---	---	.001	.001[b]	---
M2	---	---	---	---[c]	---	---[c]
M3	---[b]	---	---	---	.001[b]	---

Note. Dashes indicate a nonsignificant main effect.

[a]Significant Fitness x Footwear interaction. [b]Significant Fitness x Load interaction. [c]Significant Footwear x Load interaction.

Findings related to the footwear main effect are presented in Table 9 for both the men and the women. Instances in which the footwear effect failed to reach significance are indicated, as are the results of the post-hoc, *HSD* procedure applied to the significant effects. In the case of significance, the footwear types with the highest and the lowest means, as determined by the *HSD* procedure, are indicated.

More detailed findings from the analyses of the running parameters are presented in Appendix E. The odd-numbered tables in that appendix contain the data for the men and the even-numbered tables contain the data for the women.

Vertical Ground Reaction Force Component (Tables E-1 and E-2)

There were no significant interactions involving footwear on any of the vertical ground reaction force parameters. With regard to footwear main effects, the male data revealed that first maximum force (Fz1) and time to first maximum force (Fz2) were significantly affected by the type of footwear worn. The values of first maximum force (Fz1) for the combat and the jungle boots did not differ from each other, but they were significantly lower than the values for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. There were no other differences among the means for this parameter. For time to first maximum force (Fz2), the Reebok Pump yielded values significantly higher than those for the other footwear types. Values for the combat boot, the jungle boot, and the Rockport hiking boot were significantly lower than those for all other footwear types. There were no further significant findings on this parameter.

The female data also yielded a significant main effect of footwear on time to first maximum force (Fz2). The shortest time to first maximum force was associated with the combat boot. The mean for the combat boot differed significantly from the means for the other footwear. The longest time to first maximum force was associated with the Reebok Pump, and this mean differed significantly from the means for the remaining footwear types. There were no other significant findings on this measure. In the analyses of the female data, there was also a significant main effect of footwear on time to second maximum force (Fz4). On this parameter, the shortest times were obtained with the Reebok Pump and the Nike cross trainer. These times differed significantly from the longest time, which was achieved with the Red Wing. No other significant differences were obtained on this parameter.

Antero-posterior Ground Reaction Force Component (Tables E-3 and E-4)

Analyses of the antero-posterior ground reaction force parameters did not yield any significant second-order interactions. In addition, as was the case for marching, the male data did not reveal any significant first-order interactions involving footwear. There were two significant first-order interactions involving footwear in the analyses of the female data and both were interactions of fitness and footwear. One occurred on

Table 9. Extreme Values of Footwear Means for Overground and Treadmill Running Parameters Based on Post Hoc Analyses of Footwear Main Effect

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
	Vertical Ground Reaction Force Component			
Fz1	Com, Jun	Ree, Nik, Roc	---	---
Fz2	Com, Jun, Roc	Ree	Com	Ree
Fz3	---	---	---	---
Fz4	---	---	Ree, Nik	Red
Fz5	---	---	---	---
Fz6	---	---	---	---
	Antero-posterior Ground Reaction Force Component			
Fy1	---	---	---	---
Fy2	Com, Jun, Ree, Nik, Roc	Red	---	---
Fy3	---	---	---	---
Fy4	---	---	---	---
Fy5	---	---	---	---
	Medio-lateral Ground Reaction Force Component			
Fx1	Ree, Nik, Roc	Red	Ree, Nik, Roc	Com, Red
Fx2	Ree, Nik, Roc	Red	Ree, Nik, Roc	Com, Red
	In-shoe Pressure			
P1	---	---	Ree	Com, Jun, Nik, Roc, Red
P2	---	---	---	---
P3	---	---	Com, Nik, Roc, Red	Jun, Red

Table 9. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
	Sagittal Plane Kinematics - Hip Angle			
H1	---	---	---	---
H2	---	---	---	---
H3	---	---	---	---
H4	---	---	---	---
H5	---	---	---	---
H6	---	---	---	---
	Sagittal Plane Kinematics - Knee Angle			
K1	---	---	---	---
K2	---	---	---	---
K3	Ree, Nik, Roc	Com	---	---
K4	---	---	---	---
K5	---	---	---	---
K6	---	---	---	---
	Sagittal Plane Kinematics - Ankle Angle			
A1	Ree	Jun, Nik, Roc	Ree	Com, Jun, Nik, Roc, Red
A2[a]	Red	Ree, Roc	Com, Jun, Red	Ree
A3	Ree, Red	Nik, Roc	Com, Jun, Ree, Red	Nik, Roc
A4	Com, Jun	Nik	Com, Jun	Ree, Nik, Roc, Red
A5[a]	Ree, Nik, Roc	Com, Jun, Red	Nik	Com, Jun
A6	---	---	---	---

Table 9. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		Sagittal Plane Kinematics - Metatarsal Angle		
Mt1	Ree	Com, Jun	Ree	Jun
Mt2	---	---	---	---
Mt3	Red	Com	---	---
Mt4	---	---	---	---
		Rearfoot Movement		
Rf1	Com, Jun	Ree, Nik, Red	Com	Ree, Nik, Red
Rf2[a]	---	---	Red	Roc
Rf3	---		---	---
Rf4	Com, Jun	Ree, Nik, Roc, Red	Com, Red	Nik, Roc
Rf5[a]	---	---	Com, Ree, Red	Jun
		EMG - Medial Hamstring		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
		EMG - Rectus Femoris		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---

Table 9. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		EMG - Anterior Tibialis		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	Ree, Nik	Jun, Red	---	---
		EMG - Gastrocnemius/Soleus		
EMG1	---	---	---	---
EMG2	---	---	---	---
EMG3	---	---	---	---
		Physiological Measures		
M1	---	---	Jun, Ree, Nik	Red
M2	---	---	---	---
M3	---	---	---	---

Note. Dashes indicate a significance level of $p > .05$. Com = combat boot; Jun = jungle boot; Ree = Reebok Pump; Nik = Nike cross trainer; Roc = Rockport hiking boot; Red = Red Wing work boot.

[a]Values are highest and lowest absolute values.

maximum braking force (Fy1). The means for this interaction are presented graphically in Figure 34. The interaction appears to be attributable to the relatively low value for the Red Wing work boot in the medium fitness group and its relatively high value in the other two fitness groups.

The second significant interaction between fitness and footwear was found on maximum propelling force (Fy4). The means for this interaction are presented in Figure 35. The significant interaction appears to be attributable to the high value for the Rockport hiking boot in the low fitness group compared with its relative value in the other two fitness groups.

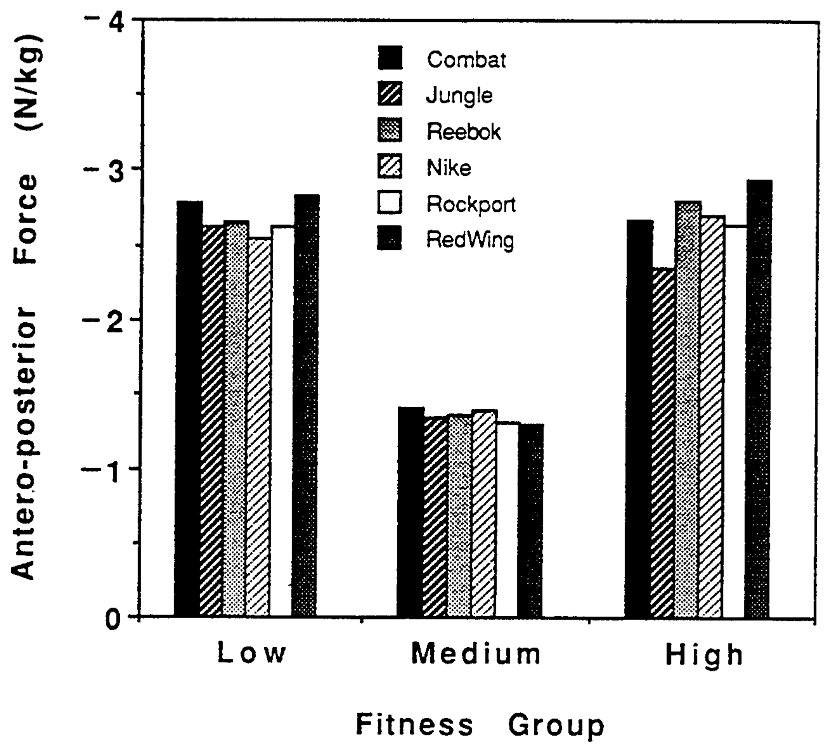

Figure 34. Means on maximum braking force (Fy1), an antero-posterior ground reaction force component, during running under each footwear condition for women within each fitness group.

In terms of footwear effects, the male data revealed a significant main effect on one parameter, time to maximum braking force (Fy2). The only significant difference was between the largest mean, which was for the Red Wing, and the means for the remaining footwear types. The female data did not yield a significant effect of footwear on any of the antero-posterior ground reaction force parameters.

Medio-lateral Ground Reaction Force Component (Tables E-5 and E-6)

No second-order interactions were significant in the analyses of the medio-lateral ground reaction force parameters, nor were any interactions between footwear and load significant. However, both the male and the female data revealed significant interactions between fitness and footwear. For the men, the interaction occurred on force excursions 0 to 30% of the contact period (Fx1). The interaction is presented in Figure 36. In all fitness groups, the Red Wing had the highest value, followed by the combat and the

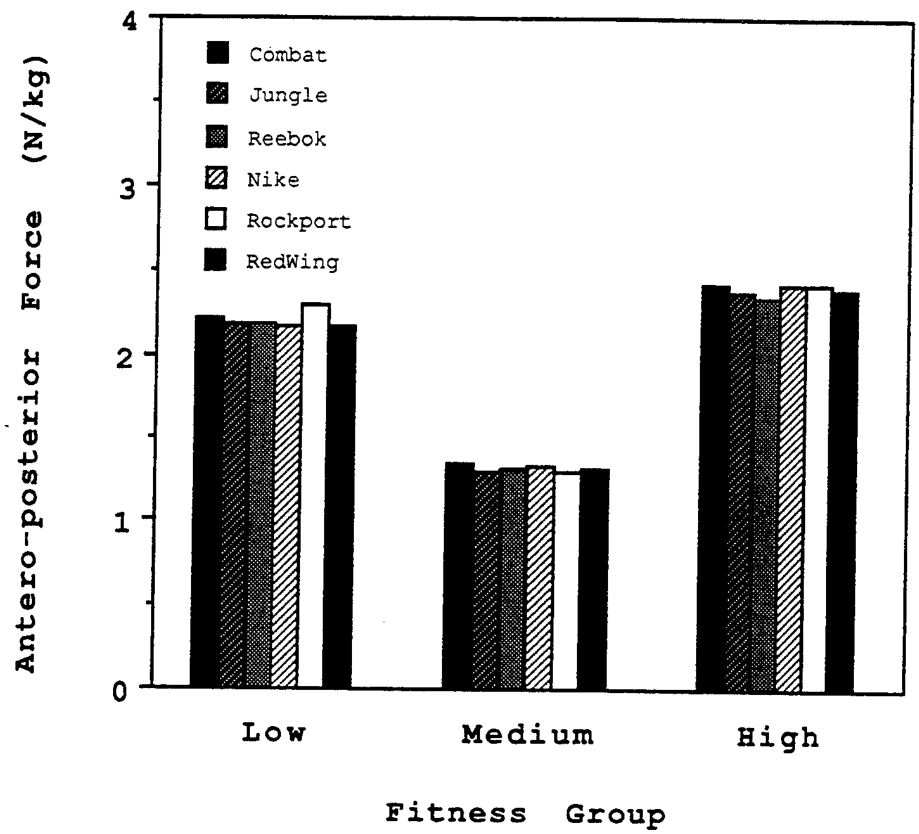

Figure 35. Means on maximum propelling force (Fy4), an antero-posterior ground reaction force component, during running under each footwear condition for women within each fitness group.

jungle boots. However, in the medium fitness group, the ranges between the values for these three footwear types and the values for the remaining footwear were less than in the low and the high fitness groups.

For the women, force excursions 0 to 30% of the contact period (Fx1) and over the entire contact period (Fx2) revealed a significant interaction between fitness and footwear. These interactions are presented graphically in Figures 37 and 38, respectively. Both interactions appear to be attributable to the relatively high value for the combat boot in the high and the low fitness groups compared with its value in the medium fitness group.

With regard to footwear main effects, the male and the female data yielded a significant finding on both medio-lateral ground reaction force parameters. For the men, the relationship among footwear conditions was the same for force excursions 0 to 30% (Fx1) and 0 to 100% (Fx2) of contact time. The mean for the Red Wing was

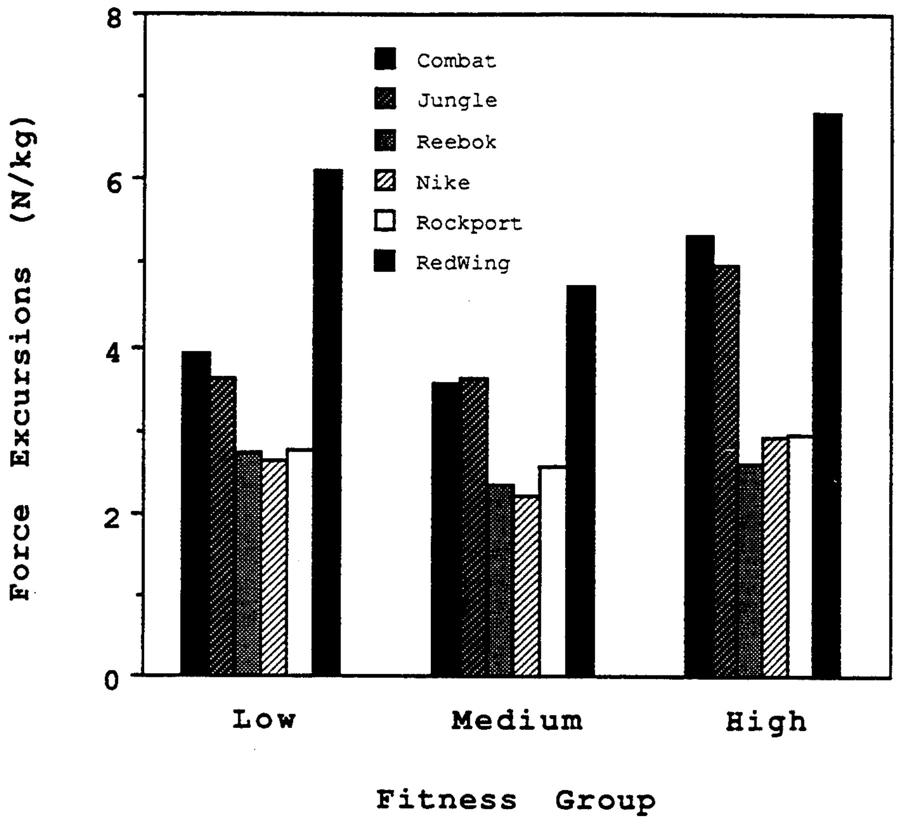

Figure 36. Means on force excursions 0-30% of contact period (Fx1), a medio-lateral ground reaction force component, during running under each footwear condition for men within each fitness group.

significantly higher than the means for the other footwear types. The means for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot did not differ from each other, but were significantly lower than the means for the other footwear types. These were the only significant differences obtained on the medio-lateral force excursion parameters.

In the analyses of the female data for force excursion 0 to 30% of contact time (Fx1), the highest means, those for the combat boot and the Red Wing, did not differ from each other. However, they were significantly different from the means for all other footwear types except the jungle boot. There were no other significant differences on this parameter. Analyses of force excursions over the entire contact period (Fx2) revealed that the highest means were again for the combat and the Red Wing work boot. These means did not differ from each other, but were significantly different from the means for the remaining footwear types. Furthermore, the lowest means, those for the Reebok

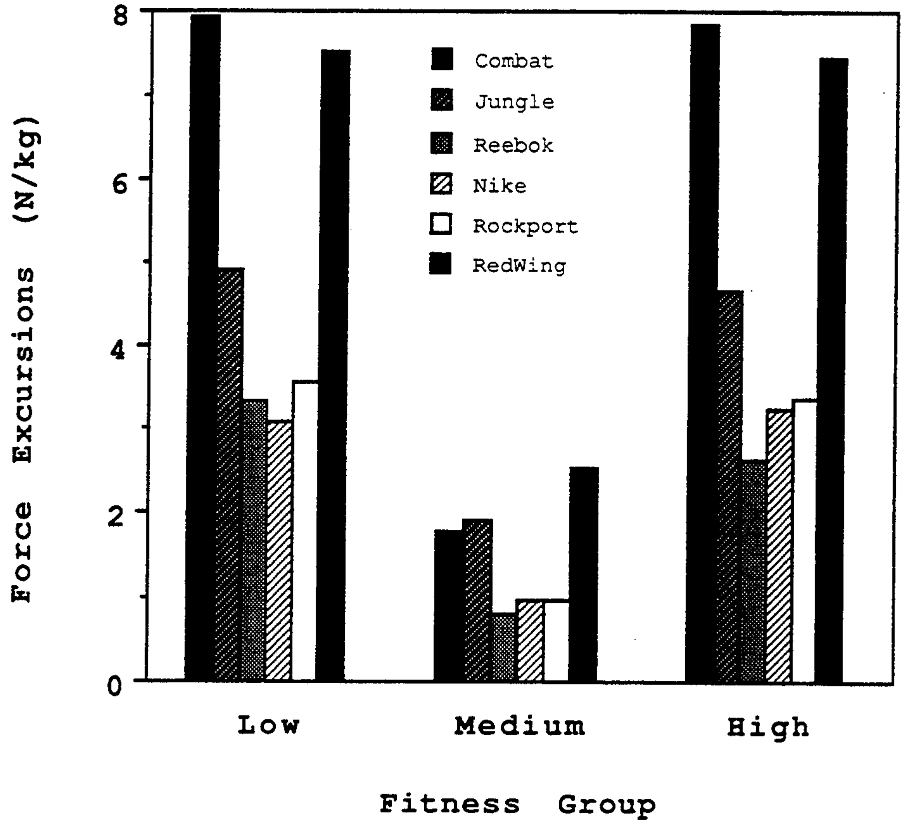

Figure 37. Means on force excursions 0-30% of contact period (Fx1), a medio-lateral ground reaction force component, during running under each footwear condition for women within each fitness group.

Pump, the Nike cross trainer, and the Rockport hiking boot, did not differ from each other, but did differ significantly from the means for the remaining footwear types. There were no other significant findings on this parameter.

In-shoe Pressure (Tables E-7 and E-8)

The analyses of the in-shoe pressure data did not yield any significant interactions, nor was footwear found to be a significant main effect in analyses of the male data. However, the female data yielded significant footwear effects on peak heel pressure (P1) and total movement distance of COP (P3). For peak heel pressure (P1), the mean for the Reebok Pump was significantly higher than the means for the other footwear conditions. No other differences were obtained on this measure. For total movement distance of COP (P3), the highest means were for the jungle boot and the Reebok Pump. These

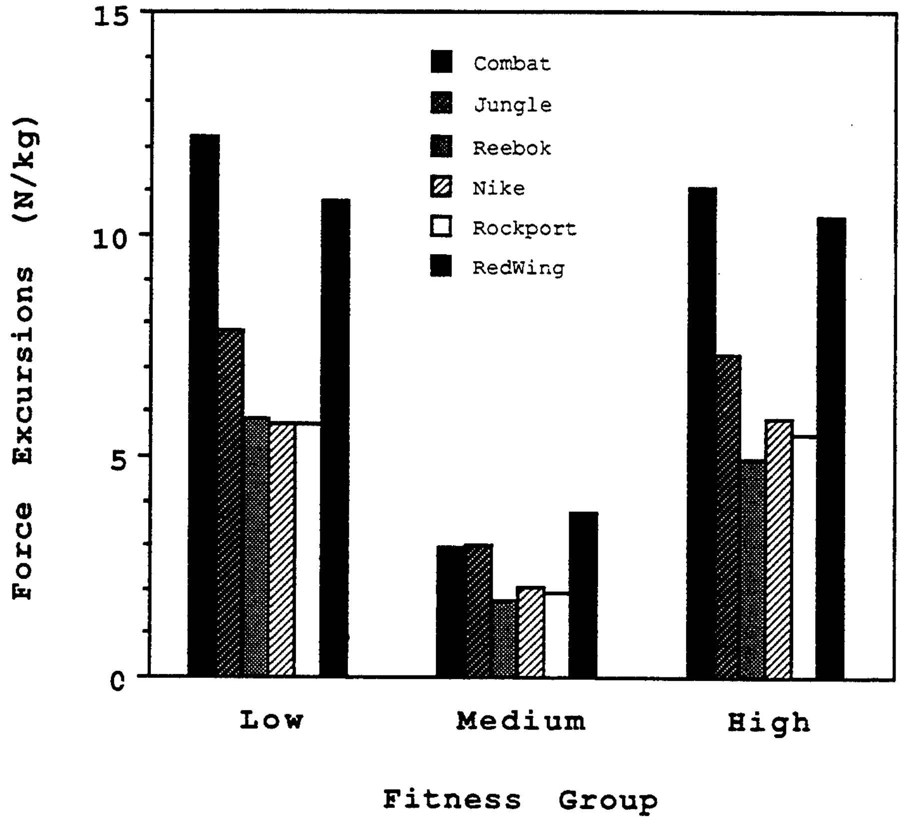

Figure 38. Means on force excursions 0-100% of contact period (Fx2), a medio-lateral ground reaction force component, during running under each footwear condition for women within each fitness group.

means did not differ from each other, but they were significantly different from the means for the other footwear types. No other differences were significant on this measure.

Sagittal Plane Kinematics

Hip angle (Tables E-9 and E-10). Analyses of the hip angle parameters did not yield any significant interactions involving footwear or any significant main effects of footwear.

Knee angle (Tables E-11 and E-12). The analyses of the knee angle parameters revealed only one significant finding involving footwear. It was a significant main effect found in the analysis of the male data for maximum flexion velocity (K3). The lowest means on this measure were achieved with the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. These means did not differ from each other, but were significantly different from the highest mean, which was achieved with the combat boot. This was the extent of the significant differences on this parameter.

Ankle angle (Tables E-13 and E-14). The second-order interaction and the interaction between footwear and load did not achieve significance in the analyses of the ankle angle data. However, both the male and the female data revealed a significant interaction between fitness and footwear on one parameter, maximum dorsiflexion (A2).

The male data for the significant interaction between fitness and footwear on maximum dorsiflexion are presented in Figure 39. The interaction appears to be attributable to the relatively high value for the Reebok Pump in the low fitness group compared with its lower value in the other two fitness groups.

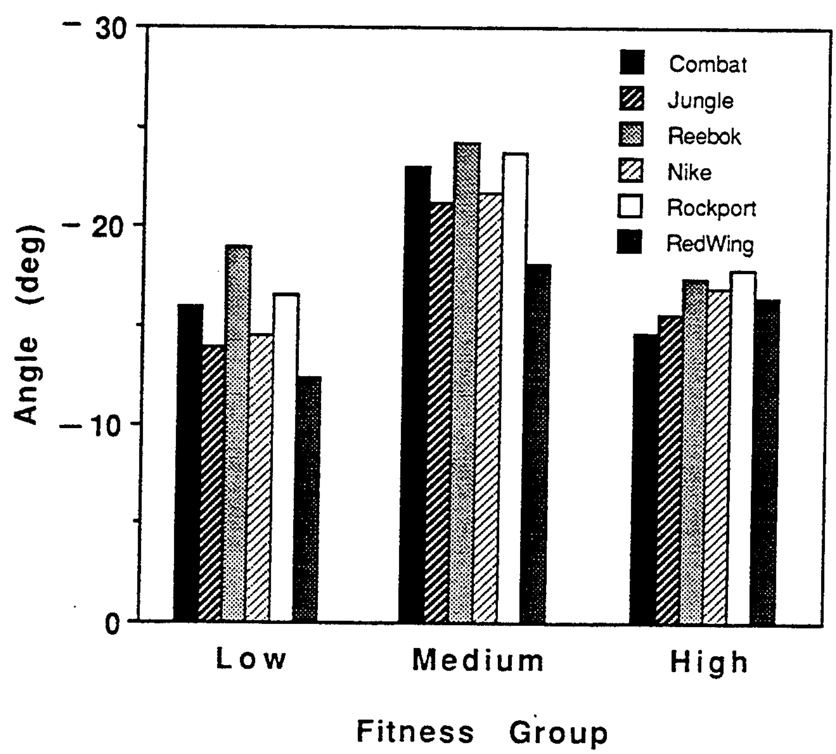

Figure 39. Means on maximum ankle dorsiflexion (A2) during running under each footwear condition for men within each fitness group.

The female data for the significant interaction between fitness and footwear on the maximum dorsiflexion measure are presented in Figure 40. The Reebok Pump had the highest mean in all fitness groups. However, the significant interaction appears to be attributable to the fact that the mean for the Reebok Pump was relatively higher than the means for the other footwear types in the medium fitness group compared with the other fitness groups.

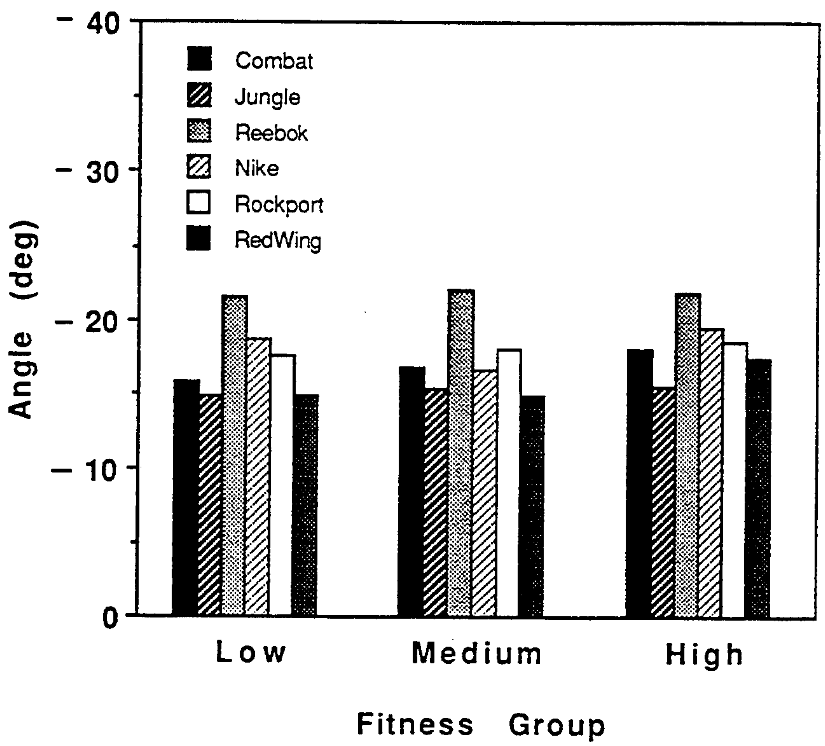

Figure 40. Means on maximum ankle dorsiflexion (A2) during running under each footwear condition for women within each fitness group.

In terms of the main effect of footwear on ankle angle parameters, analyses of the male data revealed significant findings for all parameters except time to maximum dorsiflexion velocity (A6). For the maximum plantarflexion variable (A1), the smallest mean was achieved with the Reebok Pump. It was significantly different from the largest means. These were for the jungle boot, the Nike cross trainer, and the Rockport hiking boot. There were no other significant findings on this measure. For maximum dorsiflexion (A2), a negative quantity, the smallest absolute value was for the Red Wing work boot. This value differed significantly from the values for the Reebok Pump and the Rockport hiking boot. The largest value, that for the Reebok Pump, also differed from the value for the jungle boot. There were no other significant findings on this measure. On the maximum plantarflexion velocity measure (A3), the two highest values, those for the Nike cross trainer and the Rockport hiking boot did not differ from each other, but were significantly different than the values for the remaining footwear types. Similarly, the two lowest values, those for the Reebok Pump and the Red Wing, did not differ from each other, but did differ significantly from the values for the other footwear types. There were no other significant differences on this measure. For time to maximum plantarflexion velocity (A4), the highest and the lowest means differed significantly. The highest mean was achieved with the Nike cross trainer and the lowest with the combat and the jungle boots. With regard to maximum dorsiflexion velocity (A5), a negative quantity, the absolute values for the combat boot, the jungle boot, and the Red Wing did not differ from each other, but they were significantly larger than the values for the other footwear items, which again did not differ from each other.

Like the male data, analyses of the female data revealed a significant main effect of footwear on all parameters except time to maximum dorsiflexion velocity (A6). On the maximum plantarflexion parameter (A1), the lowest mean, which was achieved with the Reebok Pump, differed significantly from the remaining means. No other differences were significant on this measure. For maximum dorsiflexion (A2), a negative quantity, the largest absolute value was for the Reebok Pump. This value differed significantly from all others. The smallest absolute value was achieved with the jungle boot. In addition to differing from the value for the Reebok Pump, this value differed from those for the Nike cross trainer and the Rockport hiking boot. On the maximum plantarflexion velocity measure (A3), the highest means differed from all others. The highest mens were associated with the Nike cross trainer and the Rockport hiking boot. There were no further significant findings on this measure. For time to maximum plantarflexion velocity (A4), the two lowest means, which were for the combat and the jungle boots, did not differ from each other, but did differ significantly from the means for the remaining footwear types. No other significant findings were obtained on this parameter. For maximum dorsiflexion velocity (A5), a negative quantity, only the highest and the lowest absolute values differed significantly. The highest absolute values were achieved with the combat and the jungle boots and the lowest with the Nike cross trainer.

Metatarsal angle (Tables E-15 and E-16). Neither the male nor the female data revealed a significant second-order interaction on any of the metatarsal angle parameters. However, there were significant first-order interactions involving footwear. The significant finding for both the male and the female data was an interaction between fitness and footwear on maximum metatarsal flexion (Mt1). The interaction means are presented graphically in Figure 41 for the men and in Figure 42 for the women.

For the men, the significant interaction between fitness and footwear on the maximum metatarsal flexion measure (Figure 41) appears to be attributable to the relationship between the highest values, those for the combat and the jungle boots. In the low fitness group, the values for these two footwear types were equal. In the medium fitness group, the jungle boot had the higher value. In the high fitness group, the combat boot had the higher value.

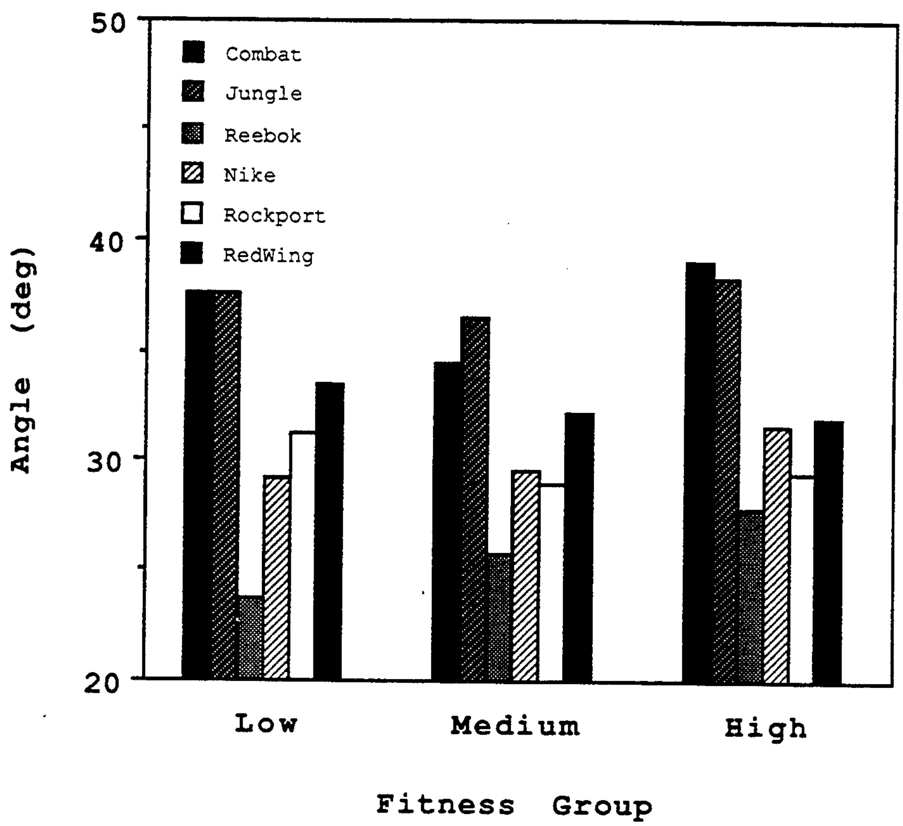

Figure 41. Means on maximum metatarsal flexion (Mt1) during running under each footwear condition for men within each fitness group.

The significant interaction between fitness and footwear on the maximum metatarsal flexion measure revealed in the analyses of the female data (Figure 42) appears to be attributable to the relationship between the lower values. For the low and the high fitness group, the means for the Reebok Pump and the Nike cross trainer are approximately equal. For the medium fitness group, the mean for the Nike cross trainer is greater than for the Reebok Pump.

In terms of footwear main effects, two parameters were found to be significant in the analyses of the male data. These were maximum flexion (Mt1) and maximum velocity (Mt3). With regard to maximum flexion (Mt1), the two highest means were

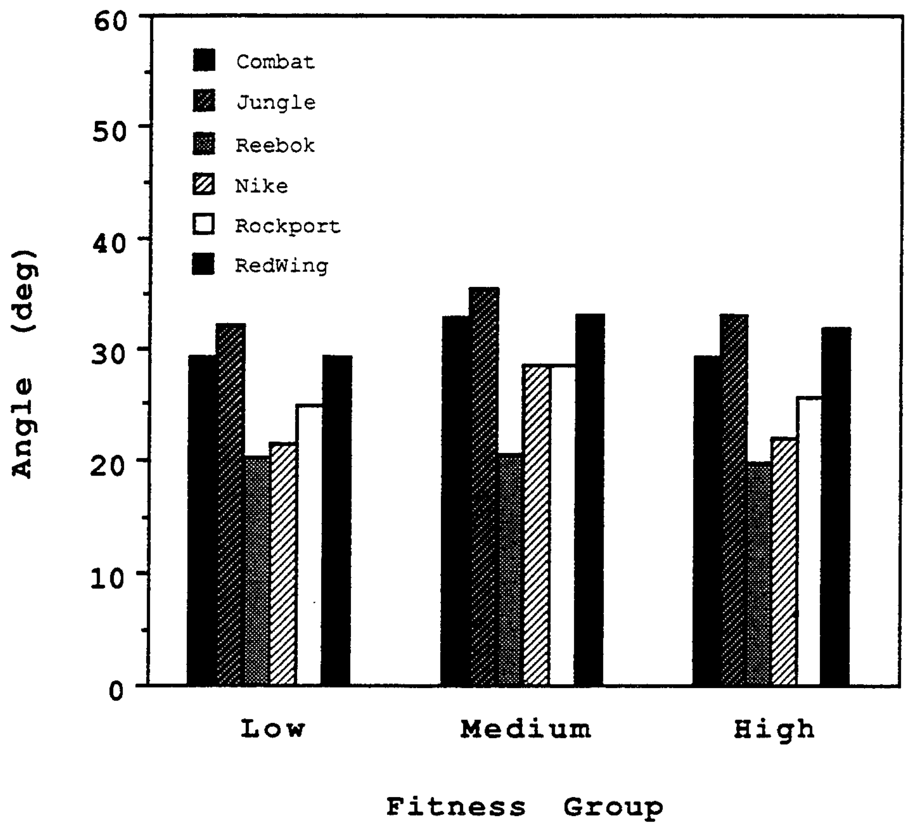

Figure 42. Means on maximum metatarsal flexion (Mt1) during running under each footwear condition for women within each fitness group.

obtained with the combat and the jungle boots. These means did not differ from each other, but did differ significantly from the means for the remaining footwear types. The lowest mean, that for the Reebok Pump, was also significantly different from the other means. No other differences were obtained on this measure. On the maximum velocity parameter (Mt3), the combat boot yielded the highest mean. The mean differed significantly from the means for the Nike cross trainer, the Rockport hiking boot, and the Red Wing. The lowest mean, that for the Red Wing, differed not only from the value for the combat boot, but also from the values for the jungle boot and the Reebok Pump. This was the extent of the significant findings on the measure.

The analyses of the female data yielded a significant footwear effect only on maximum flexion (Mt1). Here, the lowest mean, which was for the Reebok Pump, differed significantly from the means for the remaining footwear types. Next in order of increasing value, were the means for the Nike cross trainer and the Rockport hiking boot. These means did not differ from each other, but did differ significantly from the remaining means. The highest mean, that for the jungle boot, also differed significantly from the means for the remaining footwear types. No other significant findings were obtained on this measure.

Rearfoot Movement (Tables E-17 and E-18)

The analyses of the rearfoot movement parameters did not reveal any second-order interactions that were significant or any significant first-order interactions involving footwear. There were significant footwear main effects, however.

Analyses of the male data yielded a significant main effect of footwear on two rearfoot movement parameters. One of these was rearfoot angle at foot strike (Rf1). Here, the two lowest values, which were for the combat and the jungle boots, differed significantly from the values for the remaining footwear types. Also, the highest values, which were for the Reebok Pump, the Nike cross trainer, and the Red Wing, differed from the values for the remaining footwear types. No other significant findings were obtained on this measure. The other rearfoot parameter that yielded a significant main effect of footwear in analysis of the male data was total rearfoot motion (Rf4). The two lowest means on this parameter were those for the combat and the jungle boots. These means did not differ from each other, but were significantly different from the values for the remaining footwear types. No other significant findings were obtained on this parameter.

Analyses of the female data yielded significant effects of footwear on all parameters except time to maximum rearfoot angle (Rf3). For rearfoot angle at foot strike (Rf1), the highest values were achieved with the Reebok Pump, the Nike cross trainer, and the Red Wing work boot. These values did not differ from each other, but were significantly different from the values for the remaining footwear types. The lowest value was associated with the combat boot. It also differed significantly from the values for the other footwear. No further significant findings were obtained on this parameter. For maximum rearfoot angle (Rf2), the highest absolute value was achieved with the Rockport hiking boot. This value was significantly different from the lowest absolute value, which was achieved with the Red Wing. There were no other significant differences on this measure. On total rearfoot motion (Rf4), the two highest and the two lowest values differed significantly. The two highest values were associated with the Nike cross trainer and the Rockport hiking boot; the two lowest values were associated with the combat boot and the Red Wing. For maximum rearfoot velocity (Rf5), a negative quantity, the largest absolute value was associated with the jungle boot. This value differed significantly from the values for the remaining footwear types. The smallest absolute values were for the combat boot, the Reebok Pump, and the Red Wing. These values did not differ from each other. However, they were significantly different from the values for the remaining footwear types. No other findings on this measure were significant.

EMG

Medial hamstring (Tables E-19 and E-20). Analyses of the medial hamstring parameters did not yield significant interactions or significant main effects of footwear.

Rectus femoris (Tables E-21 and E-22). Analyses of the rectus femoris data did not reveal any significant interactions involving footwear or any significant footwear main effects.

Anterior tibialis (Tables E-23 and E-24). There were no significant interactions involving footwear in the analyses of the anterior tibialis parameters. Analyses of the male data yielded the only significant main effect of footwear. This was on the area under the curve parameter (EMG3). The two highest values differed significantly from the two lowest. The highest values were for the jungle boot and the Red Wing; the lowest values were for the Reebok Pump and the Nike cross trainer. There were no other significant differences among footwear types on this measure.

Gastrocnemius/soleus (Tables E-25 and E-26). Analyses of these parameters yielded only one significant finding involving the footwear variable. This was an interaction between fitness and footwear in the analysis of the female data for the time to onset of muscle activity (EMG1). The interaction is presented graphically in Figure 43. The mean values of onset time for the footwear are positive in the low fitness group, negative in the medium fitness group, and both positive and negative in the high fitness group. However, in each fitness group, the mean with the highest absolute value is the mean for the Red Wing work boot. The significant interaction appears to be attributable to the fact that the absolute value of the Red Wing mean exceeds the values of the remaining means by a greater amount in the medium fitness group than it does in the other two fitness groups.

Physiological Measures (Tables E-27 and E-28)

Only one significant interaction involving footwear was found in the analyses of the physiological measures. This was an interaction between footwear and load obtained in analysis of the female data for RER (M2). The interaction is presented in Figure 44. The significant finding appears to be attributable to the greater decrease in the values for the Rockport hiking boot and the Red Wing, compared with the other footwear types, as load was increased from 0 lb to 50 lb.

The one significant main effect of footwear was also obtained in the analysis of the female data. On the oxygen uptake measure (M1), the highest mean, which was associated with the Red Wing work boot, differed significantly from the three lowest means. These were for the jungle boot, the Reebok Pump, and the Nike cross trainer.

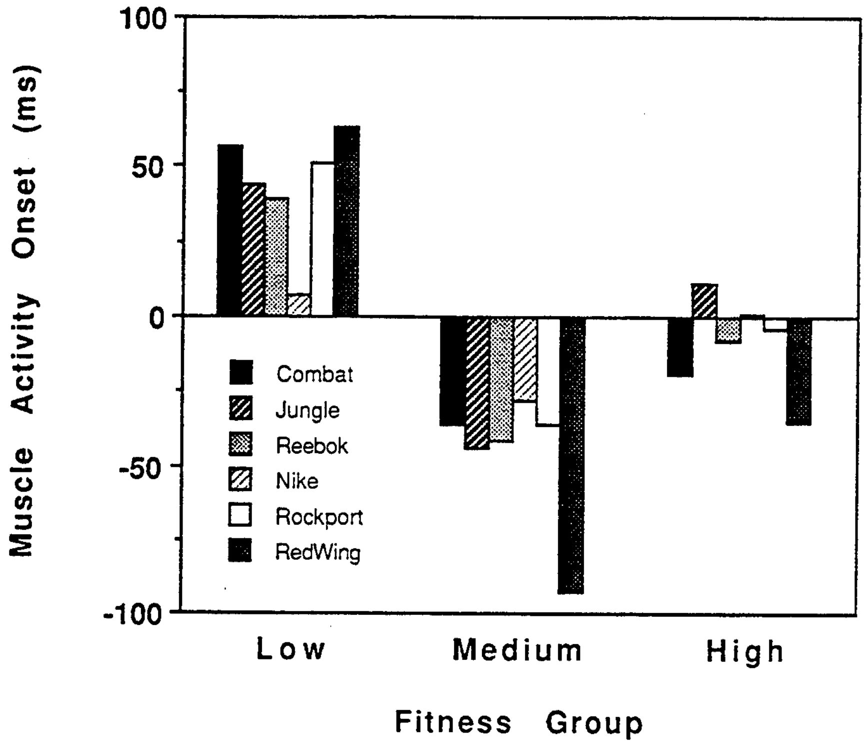

Figure 43. Means on time to onset of activity (EMG1) of the gastrocnemius/soleus during running under each footwear condition for women within each fitness group.

Discussion

The results on the first maximum vertical force parameter for running differed from the results on this parameter for the other two locomotor movements. In the analyses of walking and marching, both the male and the female data sets yielded a significant main effect of footwear; for overground running, the male data, but not the female data, revealed a significant footwear effect. Also for walking and marching, the magnitudes of first maximum vertical force with the combat and the jungle boots tended to be larger than the magnitude with the Nike cross trainer, although the values for these three footwear types did not differ significantly. For running, the male data, which, unlike the female data, yielded a significant footwear effect, indicated that the values of first maximum vertical force with the combat and the jungle boots were not only smaller than the value with the Nike cross trainer, but smaller than the values with the remaining footwear types. Furthermore, the analysis of the male data for running revealed a significant difference between the values with the military boots, the lowest values, and the values with the Nike cross trainer, the Reebok Pump, and the Rockport hiking boot, the highest values.

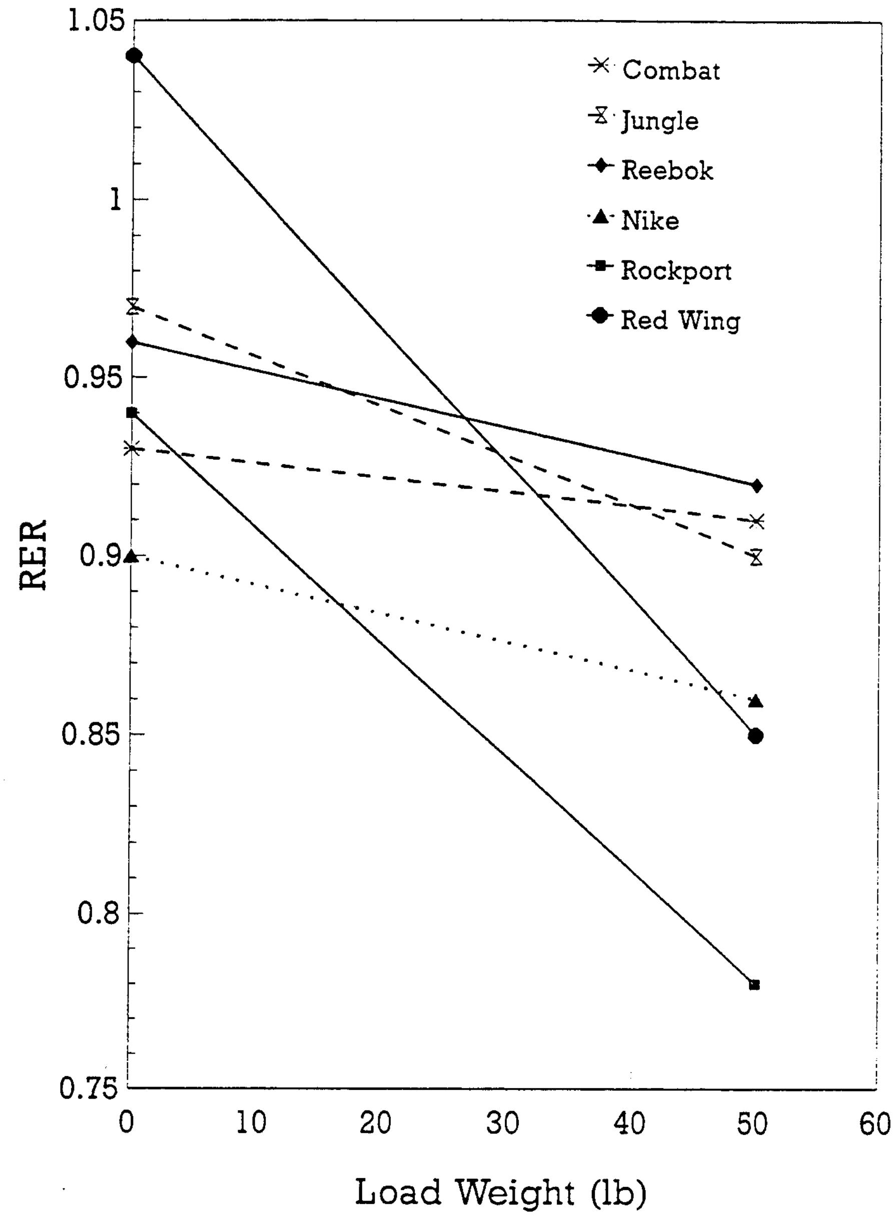

Figure 44. Means for women on RER (M2) during running under each footwear and load condition.

The findings with regard to the relatively low magnitudes of first maximum vertical force for the men during running with the military boots are unexpected in light of the materials testing results that revealed substantially higher values of peak g with the military boots than for the Nike cross trainer (Hamill and Bensel, 1992) and in light of the results for the first maximum vertical force parameter during walking and marching.

It may be that, during running, the materials in the Nike cross trainer and the other commercial items bottomed out, that is, reached maximum deformation before the peak forces between the ground and the foot were reached. Nigg et al. (1986) maintained that bottoming out could occur with soft sole materials.

The failure to obtain a significant effect of footwear on first maximum vertical force in the analysis of the female data set is in consonance with the outcome of the study of midsole hardness conducted by Clarke, Frederick, and Cooper (1983). That research focused on ground reaction force-time histories of men running in shoes differing in midsole hardness. It was found that the magnitudes of the impact peaks were unaffected by the footwear worn.

In addition to differing from walking and marching with regard to the findings for first maximum vertical force, running differed from the other locomotor movements with regard to the findings for second maximum vertical force. Both the male and the female data for walking and marching yielded a significant footwear main effect on the second maximum vertical force parameter; the military boots were associated with relatively large amplitudes of force and the Nike cross trainer with relatively small. For second maximum vertical force during running, the main effect of footwear was not significant in the analyses of either the male or the female data.

This finding is at variance with the results obtained by Clarke, Frederick, and Cooper (1983) in their study of force-time histories of men running in shoes differing in midsole hardness. In that study, the softer shoe yielded the higher propulsive or thrust peak.

As was the case for overground walking and marching, the results for overground running reflected to a limited extent the finding from the materials testing phase that the shortest times to peak g were associated with the military boots (Hamill and Bensel, 1992). During running, the men achieved the shortest times to first maximum vertical force with the combat and the jungle boots. The times for these boots did not differ from each other, but did differ significantly from the times for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. For the women, the shortest time was associated with the combat boot and this value differed significantly from the values for the other footwear types. Thus, on the time to first maximum vertical force measure during running, the male and the female data were consistent with the materials testing findings to the extent that one or both of the military boots were associated with low values.

On the other hand, the times to second maximum vertical force during running did not reflect the materials testing findings. Analysis of the male data for this measure failed to yield a significant footwear effect. Analysis of the female data did. However, the shortest times were associated with the Reebok Pump and the Nike cross trainer, not with the military boots.

Unlike overground walking and marching, analyses of in-shoe measurements of peak heel and peak forefoot pressures during running did reveal a significant finding related to footwear. This was a significant main effect of footwear obtained in the analysis of the female data for peak heel pressure. Here, the peak pressure with the Reebok Pump was significantly less than the peak pressures with the remaining footwear types, which did not differ significantly from each other. Although there was a differentiation among footwear items in this instance, the finding is not in accord with the impact test results from the materials testing phase of the research in which peak pressures with the military boots exceeded those for all commercial items tested (Hamill and Bensel, 1992). Thus, as they relate to peak pressure at the foot/shoe interface, the results for running, like those for walking and marching, revealed the performance of the military boots to be better than expected on the basis of the materials testing. Furthermore, for running, the military boots were not associated with relatively large magnitudes of vertical force during ground contact, although this was the case for walking and marching.

The knee angle data recorded during overground walking and marching indicated that maximum flexion, which occurred after toe-off, was generally greater with the military boots than with some of the commercial items, particularly the Nike cross trainer and the Rockport hiking boot. In their study of subjects running at a pace of 4.5 m/s, Clarke, Frederick, and Cooper (1983) reported increased knee flexion following foot strike with increases in midsole hardness, as measured on a durometer Shore A scale. Of the footwear tested in the present study, the items with the hardest midsoles were the military boots and the Red Wing work boot. Given the findings from the present analyses of overground walking and marching and the reports of Clarke, Frederick, and Cooper for running, it would be expected that, in the present study, the extent of knee flexion during running would be greater in the military boots and the Red Wing work boot than in the other footwear. However, neither the male nor the female data yielded a significant effect of footwear on maximum knee flexion.

The walking and the marching data also revealed differences among the footwear items in maximum knee flexion velocities, with the higher velocities being associated with the military boots. Analysis of the male running data revealed that the effect of footwear on maximum knee flexion velocity was significant and the highest velocity was achieved with the combat boot. The value for the combat boot differed significantly from the three lowest velocities, which were for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. The female data for running did not reveal a significant effect of footwear on maximum knee flexion velocity.

In the materials testing phase of this research, the combat and the jungle boots and the Red Wing work boot were found to be the least flexible of the footwear items studied (Hamill and Bensel, 1992), leading to the expectation of higher levels of muscle activity during locomotion with these items compared with the other footwear types. However, during overground walking and marching, footwear did not have a significant effect on the amplitude of the signals from any of the four muscle groups being recorded.

Analyses of the data associated with overground running, on the other hand, did yield one significant effect of footwear on muscle activity. This was in the analysis of the male data recorded from the anterior tibialis muscle group. Here, the highest amplitude signal was associated with the Red Wing work boot, followed by the jungle boot. The values for these footwear types differed significantly from the two lowest values, which were for the Reebok Pump and the Nike cross trainer. Thus, there was some limited evidence from overground running to support the materials test finding regarding forefoot flexibility differences among the footwear items. In addition, the metatarsal joint angle data for overground running, like the data for overground walking and marching, revealed that the foot was bent at the metatarsals to a greater extent in the military boots and the Red Wing work boot than it was in some of the other footwear.

The male data for the maximum metatarsal flexion measure during running revealed that the largest angles were associated with the combat and the jungle boots. The values for these boots differed significantly from the values for all other footwear types. The next highest value was for the Red Wing work boot. With regard to the female data for the metatarsal flexion angle, the jungle boot yielded a value that was significantly larger than the values for all other footwear types. The next highest values were for the combat boot and the Red Wing work boot. Both the male and the female data yielded a significant interaction between fitness and footwear on the maximum metatarsal flexion measure. However, for both genders and for all fitness groups, the highest values were associated with the military boots and the Red Wing work boot.

During walking and marching, the maximum metatarsal flexion velocities were relatively high when the military boots were worn. The male and the female data for running also showed this to be the case, with the two highest velocities being associated with the military boots. Thus, during all three locomotor movements, metatarsal flexion with the military boots described a large angular displacement and involved a high velocity movement.

Like the overground walking and marching data, the data for overground running related to rearfoot movement parameters provided some support for the finding from the materials testing that the military boots and the Red Wing work boot are highly stable compared with the other footwear studied (Hamill and Bensel, 1992). On the maximum rearfoot angle measure, the male data did not yield a significant footwear effect; the female data did, and the Red Wing work boot resulted in the smallest angular excursion. The value for the Red Wing work boot differed significantly from the largest value, which was associated with the Rockport hiking boot. This finding of small angular values for the Red Wing work boot is compatible with the materials testing results. However, for both the male and the female data sets, the maximum rearfoot angles with the military boots did not differ from the angle with any of the other footwear items, which is unexpected given the outcome of the materials testing. It is unexpected, as well, in light of the high midsole hardness values for the military boots and the finding of Clarke, Frederick, and Hamill (1983) that harder midsoles were associated with less maximum pronation.

Clarke, Frederick, and Hamill (1983) also found less total rearfoot movement in the harder shoes. Differences among footwear items in the present study were in this direction. For the men, the military boots yielded values of total rearfoot motion that were significantly lower than the values for the remaining footwear items. For the women, the lowest values were associated with the combat boot and the Red Wing work boot. The values differed significantly from the highest values, which were for the Nike cross trainer and the Rockport hiking boot.

In their study of rearfoot movement parameters during running, Clarke, Frederick, and Hamill (1983) did not find differences in rearfoot angle at foot strike among shoes with midsole hardness readings of 25, 35, and 45 durometers on the Shore A scale. However, Nigg et al. (1987) reported larger angles at foot strike as midsole hardness was increased from a Shore A reading of 25 to 45 durometers. The hardness readings for all footwear in this study exceeded those of the shoes tested by these researchers.

The minimum reading in this study was 55 durometer for the Nike cross trainer; the highest readings were 84 durometer for the jungle boot and 85 durometer for both the combat boot and the Red Wing work boot. The results regarding rearfoot angle at foot strike differ from those of Clarke, Frederick, and Hamill (1983), as well as from those of Nigg et al. (1987). In the case of both the men and the women, the combat and the jungle boots resulted in small angular excursions compared with other footwear tested. For the men, the two lowest values were associated with the military boots; they differed significantly from those for all other footwear types. For the women, the value for the combat boot was lowest and the value for the jungle boot was among the lowest. Analysis of the female data revealed that the values for both military boots differed significantly from the values for the Reebok Pump, the Nike cross trainer, and the Red Wing work boot.

During walking and marching, the male data for maximum braking force, one of the antero-posterior ground reaction force variables, was significantly affected by footwear. In the analysis of the male data for running, the effect of footwear on maximum braking force failed to reach significance. However, the female data for maximum braking force during running yielded a significant interaction between footwear and fitness group, as was also found during walking and marching. In the low fitness group, the forces of the largest amplitude during running were associated with the combat boot and the Red Wing work boot. In the medium fitness group, the forces for the footwear types were approximately equal. In the high fitness group, the forces of the highest amplitude were associated with the combat boot, the Reebok Pump, and the Red Wing work boot.

For walking and marching, analyses of the male and the female data for relative time to maximum braking force yielded a significant main effect of footwear. For running, only the analysis of the male data did. As with walking and marching, the shortest times to maximum braking force during running were associated with the Nike cross trainer and the longest with the Red Wing work boot. The time for the Red Wing work boot differed significantly from the times from all other footwear types, which did not differ from each other.

During walking and marching, maximum propelling force was not affected by the footwear worn. The results for running did yield one significant finding on this measure. It was an interaction between footwear and fitness in the analysis of the female data. In the low fitness group, the force of the highest amplitude was achieved with the Rockport hiking boot. In the remaining fitness groups, force amplitude with the combat boot was slightly higher than the amplitudes with the other footwear types. With regard to relative time to maximum propelling force, both the male and the female data revealed a significant footwear effect during walking and the female data, but not the male, revealed a significant footwear effect during marching. For running, however, neither the male nor the female data yielded a significant finding on this measure.

The findings related to the antero-posterior ground reaction force variables for running are not clear-cut in terms of the positive and negative aspects of the military boots relative to the other footwear tested. The male data for both maximum braking and maximum propelling force did not reflect significant differences among footwear types. The female data for the maximum braking and the maximum propelling forces yielded a significant interaction between footwear and fitness group. For those fitness groups in which the force magnitudes differed, the larger magnitude forces were associated with the combat boot.

The ankle angle data recorded during walking and marching did not indicate a direct relationship between the height of the footwear upper and the maximum plantarflexion angle. This was also the case with the data recorded during running. Analyses of both the male and the female data for maximum plantarflexion angle during running yielded a significant footwear effect; the lowest value was obtained with the Reebok Pump and highest with the Nike cross trainer. For the men, the angle with the

Reebok Pump differed significantly from the angles with the jungle boot, the Nike cross trainer, and the Rockport hiking boot. For the women, the angle with the Reebok Pump differed significantly from the angles with all other footwear types.

Maximum plantarflexion velocity during walking and marching revealed that the lowest values were associated with the military boots and the Red Wing work boot, the three footwear types with the highest uppers, and the highest values were for the Nike cross trainer and the Rockport hiking boot, the footwear with the lowest uppers. During running, the highest maximum plantarflexion velocities were again achieved with the Nike cross trainer and the Rockport hiking boot and the velocities with the combat boot and the Red Wing work boot were again among the lowest. However, the value for the jungle boot was relatively high.

Maximum dorsiflexion angle during running was significantly affected by footwear in the analyses of both the male and the female data. As was found on this measure during walking and marching, the extent of angular excursion during running did not vary directly with the height of the footwear upper. In both the male and the female data sets for running, the largest maximum dorsiflexion angle occurred with the Reebok Pump. For the men, the smallest angle was associated with the Red Wing work boot; for the women, the smallest dorsiflexion angle was associated with the jungle boot. In the case of the women, but not the men, the three smallest angles were achieved with the three footwear types with the highest uppers and the three largest angles were achieved with the three footwear types with the lowest uppers.

Analysis of both the male and the female data for maximum dorsiflexion velocity during running yielded a significant footwear effect. As was the case during walking and marching, velocity did not vary in an ordered fashion with upper height. However, the greatest negative magnitudes of joint angular velocities, indicating the greatest loading on the ankle joint, were achieved with the combat and the jungle boots.

With regard to the effects of footwear mass on the energy cost of locomotion, the treadmill walking and marching data for oxygen consumption and heart rate did not indicate differences related to footwear mass. This was also the case for treadmill running. The only significant finding occurred in the analysis of the female data for oxygen consumption. Here, one of the lowest values was associated with the heaviest footwear, the jungle boot. The values for the jungle boot, the Reebok Pump, and the Nike cross trainer did not differ from each other, but were significantly different from the highest value, that for the Red Wing work boot.

Considering the overall findings for running in light of the results from the walking and the marching activities, perhaps the most remarkable difference lies in the results for the military boots on vertical ground reaction force parameters. During running, unlike walking and marching, first maximum vertical forces with the military boots were of relatively low magnitude and second maximum vertical forces with the military boots did not differ from those with the other footwear types. Furthermore, during running, knee flexion angles were not more extreme with the military boots than they were with the other footwear. However, the shortest times to first maximum vertical force and the highest knee flexion velocities were associated with the military boots. As was the case during walking and marching, data for the metatarsal joint indicated greater angular excursions about the joint during running with the military boots, and the velocity of the movement was relatively high. Ankle dorsiflexion during running was limited with the military boots and was associated with relatively large negative magnitudes of angular velocity, findings in consonance with the results from the walking and the marching activities. Furthermore, like walking and marching, running revealed evidence of less movement of the calcaneus relative to the lower leg in the military boots compared with some of the other footwear types.

Jump/Landings

Results for Jump/Landings From 0.32 m

Summary

Interactions found to be significant in the analyses of the male and the female data for jump/landings from 0.32 m are indicated in Table 10. As was the case for walking, marching, and running, analyses of the jump/landing parameters did not reveal any significant second-order interactions. There were, however, first-order interactions involving footwear. The male data revealed significant interactions between fitness and footwear on maximum hip flexion velocity (LH3), maximum dorsiflexion velocity at the ankle (LA3), and time to beginning of activity of the medial hamstring muscle group (LEMG1). For the women, there were significant interactions between fitness and footwear only on slope of first maximum vertical force (LFz3). The female data revealed the only interactions between footwear and load that were significant. These occurred on maximum knee flexion (LK1) and time to beginning of activity of the anterior tibialis muscle group (LEMG1).

A summary of the significance levels of the main effects for each of the jump/landing parameters is presented in Table 10. As indicated in the table, footwear had a significant main effect on many of the measures captured during the jump/landings from 0.32 m. However, there were again some categories of measures in which none of the parameters was significantly affected by footwear. For the men, these were the hip and the knee angle kinematics and the activity of the four muscle groups. For the

Table 10. Significance of Main Effects and Summary of Significant Interactions in the Analyses of Jump/Landings From 0.32 m

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Vertical Ground Reaction Force Component			
LFz1	---	---	.001	.001	---	---
LFz2	---	---	.001	.001	---	.005
LFz3	---	---[a]	.001	.001[a]	---	---
LFz4	---	---	---	.001	---	---
LFz5	---	---	.001	.001	---	.001
LFz6	---	---	---	.001	---	---
			In-shoe Pressure			
LP1	---	---	---	---	---	.001
LP2	---	---	---	---	---	---
LP3	---	---	.005	---	---	---

Table 10. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
Sagittal Plane Kinematics - Hip Angle						
LH1	---	---	---	---	---	.001
LH2	---	---	---	---	---	---
LH3	.005[a]	---	---[a]	---	---	---
LH4	---	---	---	---	---	---
Sagittal Plane Kinematics - Knee Angle						
LK1	---	---	---	---[c]	---	---[c]
LK2	---	---[b]	---	---	---	.001[b]
LK3	---[b]	---	---	---	.001[b]	---
LK4	---	---	---	.005	---	---
Sagittal Plane Kinematics - Ankle Angle						
LA1	---	---	---	.01	---	---
LA2	---	---	---	---	---	.001
LA3	---[a]	---	.005[a]	.005	---	---
LA4	---	---	---	---	---	---

Table 10. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
Sagittal Plane Kinematics - Metatarsal Angle						
LMt1	---	---	---	.001	---	---
LMt2	---	---	.001	.005	---	---
LMt3	---	---	.001	.001	---	---
LMt4	---	---	---	---	---	---
Rearfoot Movement						
LRf1	---	---	.001	---	---	---
LRf2	---	---	---	.005	---	---
LRf3	---	---	---	---	.005	---
LRf4	---	---	.001	---	.01	---
LRf5	---	---	.001	---	.005	.001
EMG - Medial Hamstring						
LEMG1	---[a]	---	---[a]	---	---	---
LEMG2	---	---	---	---	.01	---
LEMG3	---	---	---	---	---	.001

Table 10. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			EMG - Rectus Femoris			
LEMG1	---	---	---	---	---	---
LEMG2	---	---	---	.001	---	.001
LEMG3	---[b]	---	---	---	.001[b]	.001
			EMG - Anterior Tibialis			
LEMG1	---	---	---	---[c]	---	---[c]
LEMG2	---	---	---	---	.001	---
LEMG3	---	---	---	---	---	.001
			EMG - Gastrocnemius/Soleus			
LEMG1	---	---	---	---	---	.005
LEMG2	---	---	---	---	---	.001
LEMG3	---	---	---	---	---	---

Note. Dashes indicate a nonsignificant main effect.

[a]Significant Fitness x Footwear interaction. [b]Significant Fitness x Load interaction. [c]Significant Footwear x Load interaction.

women, none of the parameters associated with in-shoe pressure, hip angle kinematics, and the activity of the medial hamstring, the anterior tibialis, and the gastrocnemius/soleus muscle groups reflected a significant main effect of footwear.

Findings related to the footwear main effect are presented in Table 11 for the men and the women. The results of the post-hoc, *HSD* procedure applied to each footwear effect that was significant are included in the table. The footwear types with the highest and the lowest means, as determined by the *HSD* procedure, are indicated. Instances in which the footwear effect failed to reach significance are also indicated.

More detailed findings from the analyses of the jump/landings from 0.32 m are presented in Appendix F. The odd-numbered tables contain the data for the men and the even-numbered tables contain the data for the women.

Vertical Ground Reaction Force Component (Tables F-1 and F-2)

Analyses of the vertical ground reaction force parameters yielded only one significant interaction involving footwear. This was an interaction between fitness and footwear found in the analysis of the female data for slope of first maximum force (LFz3). The interaction means are presented graphically in Figure 45. The highest mean in each fitness group was associated with the Red Wing work boot. The interaction appears to be attributable to the fact that the mean for the Red Wing exceeded the means for the remaining footwear types by a greater amount in the medium fitness group than in the other two fitness groups.

With regard to footwear effects, the male data yielded a significant finding on all parameters except impact ratio (LFz4) and time to second maximum force (LFz6). The highest values of first maximum force (LFz1) were achieved with the Red Wing. These values were significantly different from the two lowest values, which were achieved with the Reebok Pump and the Nike cross trainer. There were no other differences among the means on this parameter. For time to first maximum force (LFz2), the lowest value, that for the Red Wing work boot, differed significantly from the two highest values, which were associated with the jungle boot and the Reebok Pump. No further significant findings were obtained. On the slope of the first maximum force (LFz3), the value for the Red Wing was significantly higher than the values for all footwear types except the combat boot. The values for the Reebok Pump and the Nike cross trainer were significantly lower than the values for all footwear except the jungle boot and the Rockport hiking boot. No other differences were significant on this measure. On second maximum force (LFz5), the two highest values, those for the combat boot and the jungle boot, did not differ from each other or from the value for the Red Wing work boot. However, they were significantly different from the three lowest values, those for the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. The lowest values did not differ from each other or from the mean for the Red Wing.

Table 11. Extreme Values of Footwear Means Based on Post Hoc Analyses of Footwear Main Effect for Parameters of Jump/Landings From 0.32 m

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
		Vertical Ground Reaction Force Component		
LFz1	Ree, Nik	Red	Nik	Com, Red
LFz2	Red	Jun, Ree	Red	Jun
LFz3	Ree, Nik	Red	Jun, Ree, Nik	Red
LFz4	---	---	Com, Nik, Red	Jun, Ree
LFz5	Ree, Nik, Roc	Com, Jun	Nik, Roc, Red	Jun
LFz6	---	---	Com, Jun, Red	Ree, Nik, Roc
		In-shoe Pressure		
LP1	---	---	---	---
LP2	---	---	---	---
LP3	Com, Jun	Ree, Roc	---	---
		Sagittal Plane Kinematics - Hip Angle		
LH1	---	---	---	---
LH2	---	---	---	---
LH3	---	---	---	---
LH4	---	---	---	---
		Sagittal Plane Kinematics - Knee Angle		
LK1	---	---	---	---
LK2	---	---	---	---
LK3	---	---	---	---
LK4	---	---	Red	Ree

Table 11. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
Sagittal Plane Kinematics - Ankle Angle				
LA1[a]	---	---	Jun, Red	Com, Ree, Nik, Roc
LA2	---	---	---	---
LA3[a]	Com, Jun, Red	Ree, Nik, Roc	Red	Nik
LA4	---	---	---	---
Sagittal Plane Kinematics - Metatarsal Angle				
LMt1	---	---	Com, Ree, Nik, Roc	Jun, Red
LMt2	Jun, Ree, Nik, Roc	Red	Jun, Ree, Nik	Com, Roc, Red
LMt3	Com, Red	Jun, Ree, Nik, Roc	Com, Roc, Red	Jun, Ree, Nik
LMt4	---	---	---	---
Rearfoot Movement				
LRf1	Com, Jun, Ree, Roc, Red	Nik	---	---
LRf2	---	---	Roc	Com, Jun, Nik, Red
LRf3	---	---	---	---
LRf4	Com	Jun, Ree, Nik, Roc, Red	---	---
LRf5[a]	Com	Ree, Nik, Roc	---	---
EMG - Medial Hamstring				
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---

Table 11. Continued

Parameter	Men		Women	
	Lowest	Highest	Lowest	Highest
		EMG - Rectus Femoris		
LEMG1	---	---	---	---
LEMG2	---	---	Com	Jun, Ree, Nik, Roc, Red
LEMG3	---	---	---	---
		EMG - Anterior Tibialis		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---
		EMG - Gastrocnemius/Soleus		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---

Note. Dashes indicate a significance level of $p > .05$. Com = combat boot; Jun = jungle boot; Ree = Reebok Pump; Nik = Nike cross trainer; Roc = Rockport hiking boot; Red = Red Wing work boot.

[a]Values are highest and lowest absolute values.

The female data yielded significant effects of footwear on all vertical force parameters. The highest values for first maximum force (LFz1) were achieved with the combat boot and the Red Wing. These values were significantly different from the lowest value, which was achieved with the Nike cross trainer. No other differences were obtained on this measure. The shortest mean time to first maximum force (LFz2) was associated with the Red Wing. This mean time differed significantly from all other means. The two next lowest values were for the combat boot and the Rockport hiking boot. These values did not differ from each other or from the mean for the Nike cross trainer. The longest mean time was achieved with the jungle boot. This mean differed from all others except that for the Reebok Pump. No further findings on this measure were significant. On the slope of the first maximum force (LFz3), the mean for the Red

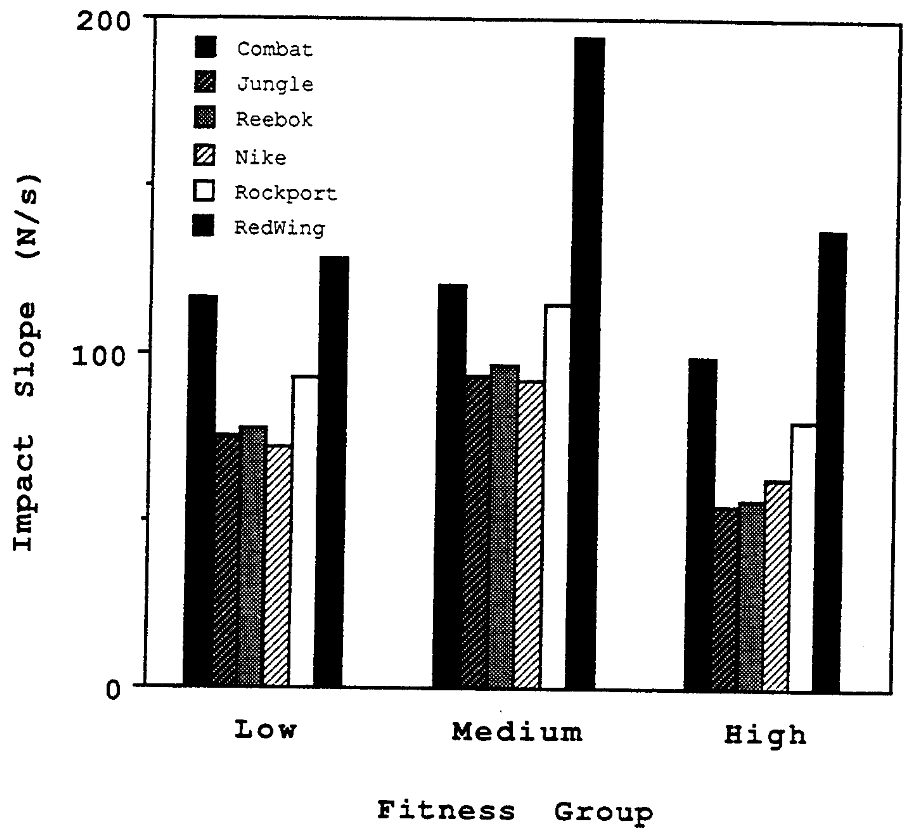

Figure 45. Means on slope of first maximum force (LFz3), a vertical ground reaction force component, during 0.32-m jump/landings under each footwear condition for women within each fitness group.

Wing was significantly higher than the means for the other footwear types. The means for the jungle boot, the Reebok Pump, and the Nike cross trainer were significantly lower than the means for all other footwear. No other differences on this measure were significant. On the impact ratio parameter (LFz4), the means for the combat boot, the Nike cross trainer, and the Red Wing were lowest. These means differed significantly from the two highest means, which were associated with the jungle boot and the Reebok Pump. There were no other significant differences among means on this parameter. With regard to second maximum force (LFz5), the jungle boot resulted in the highest mean. This mean differed from all others except that for the combat boot. The three lowest means were for the Nike cross trainer, the Rockport hiking boot, and the Red Wing work boot. These means did not differ from each other or from the mean for the Reebok Pump. No other findings on this measure were significant. For time to second maximum force (LFz6), the three lowest values did not differ from each other, but were significantly different from the three highest values, which in turn did not differ. The lowest values were achieved with the combat boot, the jungle boot, and the Red Wing.

In-shoe Pressure (Tables F-3 and F-4)

The analyses of the in-shoe pressure data did not yield any significant interactions involving footwear and there was only one main effect of footwear that was significant. The significant finding occurred in the male data for total movement distance of COP (LP3). The two largest and the two smallest means on this measure differed. The largest means were for the Reebok Pump and the Rockport hiking boot; the smallest were for the combat and the jungle boots. No other differences were obtained on this parameter.

Sagittal Plane Kinematics

Hip angle (Tables F-5 and F-6). The only significant finding involving footwear on the hip angle measure was a significant interaction between fitness and footwear on the male maximum flexion velocity parameter (LH3). The means for this interaction are presented graphically in Figure 46. The significant interaction appears to be attributable to the relatively high mean for the Red Wing in the low and the medium fitness groups and the relatively low mean for this footwear in the high fitness group.

Knee angle (Tables F-7 and F-8). The knee angle data yielded one significant interaction involving footwear. This was an interaction between footwear and load in the analysis of the female data for maximum flexion (LK1). The interaction is presented graphically in Figure 47. The significant interaction appears to be attributable to the relatively low mean for the Rockport hiking boot under the no-load condition and the relatively high mean under the 50-lb load condition.

In terms of footwear main effects, analyses of the male data did not yield any significant findings. However, the female data yielded significant findings on one parameter, time to maximum flexion velocity (LK4). The mean for the Red Wing was significantly lower than the means for the remaining footwear conditions and the mean for the Reebok Pump was significantly higher. No other significant differences were obtained on this parameter.

Ankle angle (Tables F-9 and F-10). The ankle angle parameters yielded one significant interaction involving footwear. It was an interaction between fitness and footwear found in the analysis of the male data for maximum dorsiflexion velocity (LA3). The interaction, which is presented in Figure 48, appears to be due to the fact that the highest absolute value in the medium and the high fitness groups was for the Rockport hiking boot, whereas the highest absolute value for the low fitness group was for the Nike cross trainer.

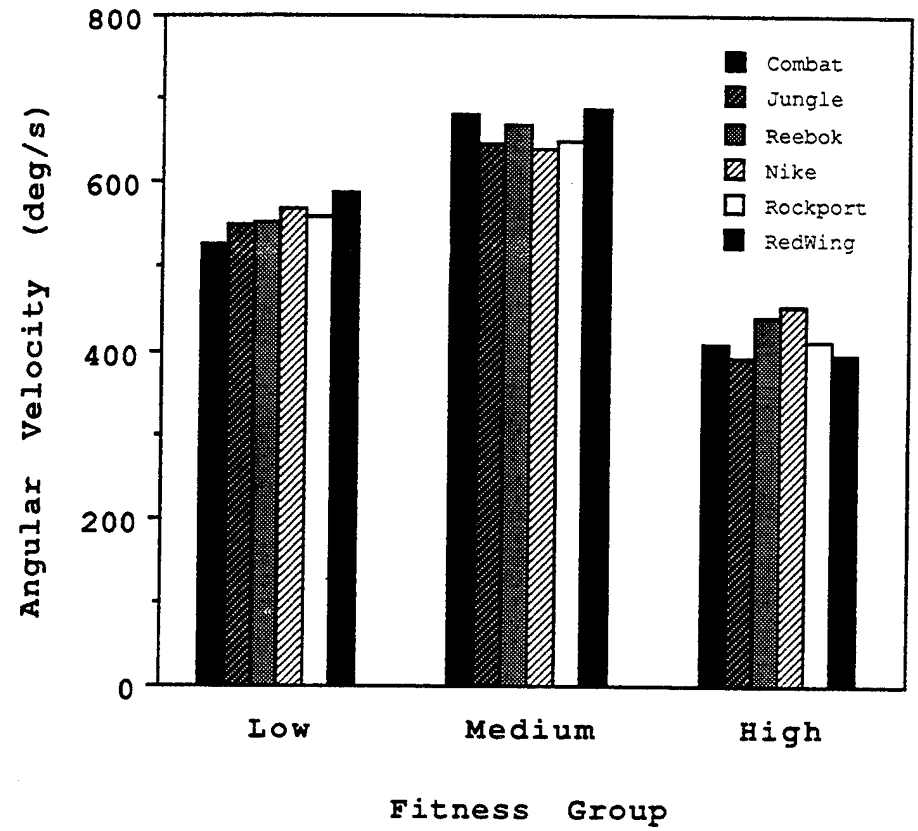

Figure 46. Means on maximum hip flexion velocity (LH3) during 0.32-m jump/landings under each footwear condition for men within each fitness group.

In terms of the effects of footwear on ankle angle parameters, analyses of the male data revealed significant findings on one parameter, maximum dorsiflexion velocity (LA3), a negative quantity. Here, the highest absolute values were achieved with the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. These values did not differ from each other, but were significantly different from the values for the remaining footwear types. There were no other significant differences on this measure.

Analyses of the female data revealed a significant main effect of footwear on two parameters. These were maximum dorsiflexion (LA1) and maximum dorsiflexion velocity (LA3), both negative measures. On the maximum dorsiflexion parameter (LA1), the two lowest absolute values did not differ from each other, but did differ significantly from the remaining means. The lowest means were for the jungle boot and the Red Wing. No further significant findings were obtained on this measure. For maximum dorsiflexion velocity (LA3), also a negative quantity, the highest and the lowest absolute

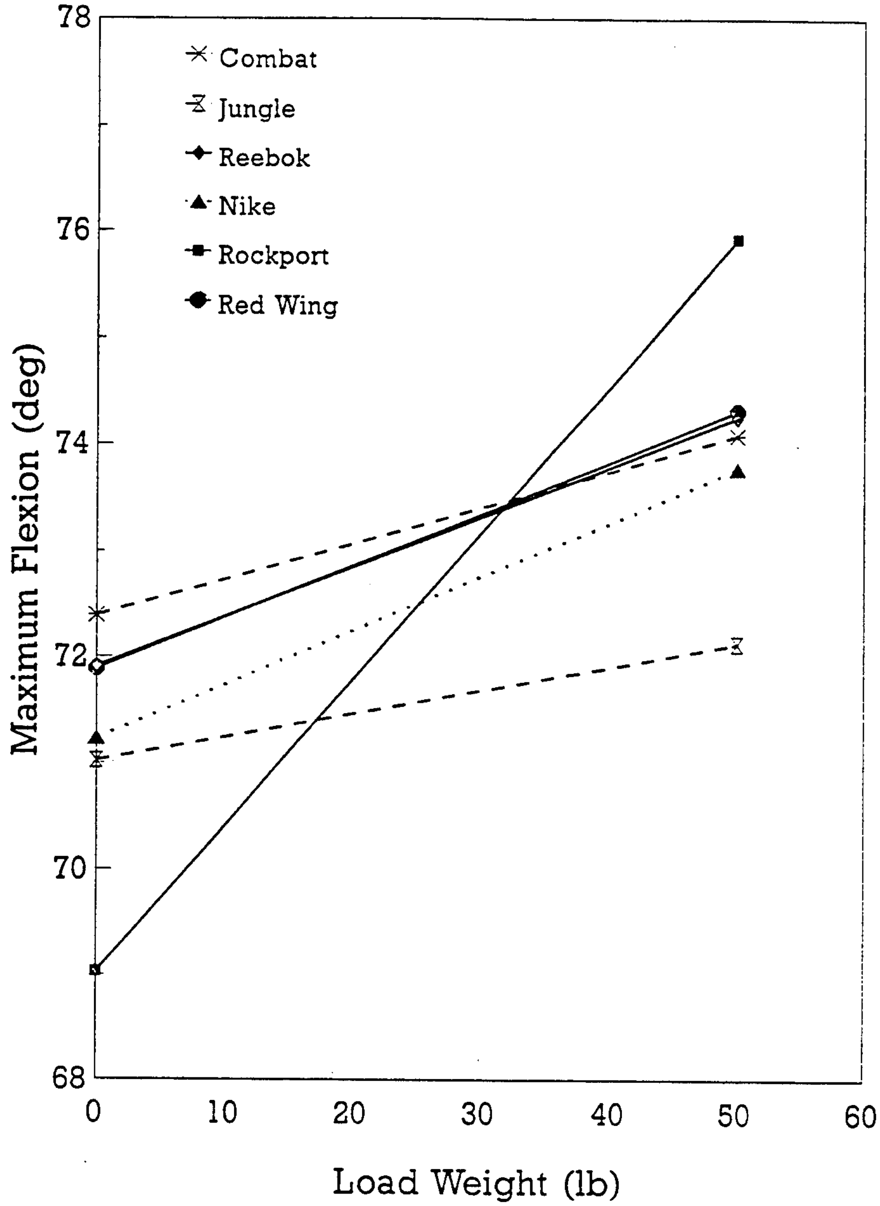

Figure 47. Means for women on maximum knee flexion (LK1) during 0.32-m jump/landings under each footwear and load condition.

values differed significantly. The highest values were for the Nike cross trainer and the lowest were for the Red Wing. No other significant findings were obtained on this parameter.

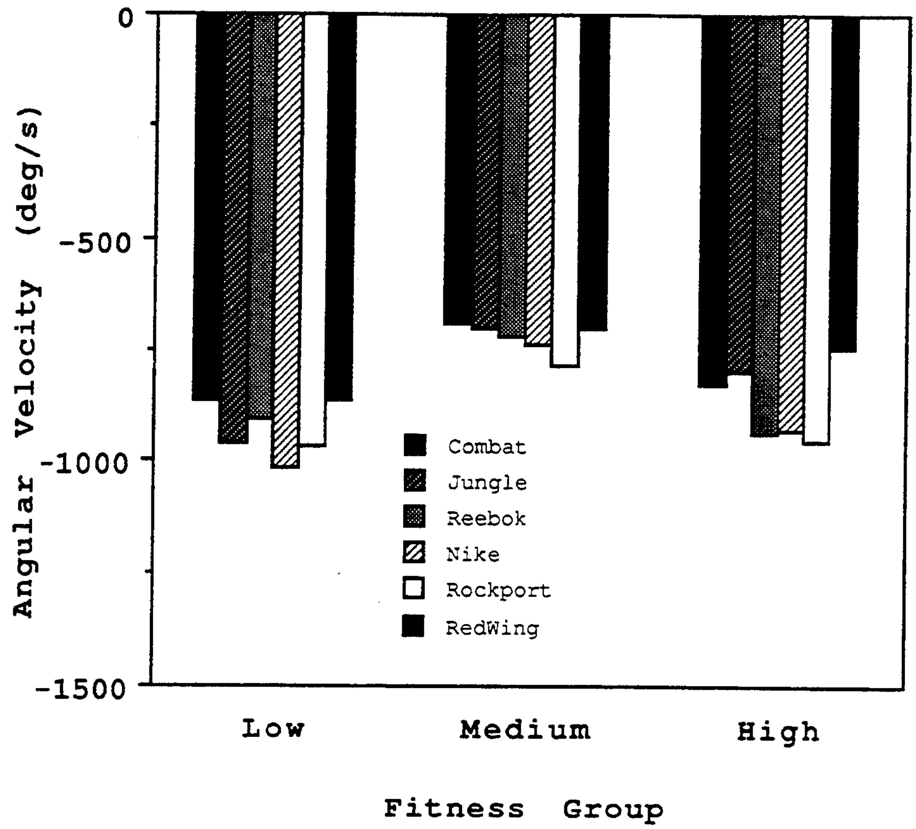

Figure 48. Means on maximum ankle dorsiflexion velocity (LA3) during 0.32-m jump/landings under each footwear condition for men within each fitness group.

Metatarsal angle (Tables F-11 and F-12). There were no significant interactions on this measure. In terms of footwear main effects, two parameters were found to be significant in the analyses of the male data. These were time to maximum flexion (LMt2) and maximum flexion velocity (LMt3). With regard to time to maximum flexion (LMt2), the mean for the Red Wing was significantly higher than the means for the other footwear types. The next highest mean was for the combat boot. This mean also differed from the means for the remaining footwear types. There were no other differences on this parameter. On the maximum flexion velocity parameter (LMt3), the lowest means were for the combat boot and the Red Wing. These means did not differ, but were significantly lower than the means for the remaining footwear types. No other differences were obtained on this measure.

The analyses of the female data yielded significant footwear effects on all parameters except time to maximum flexion velocity (LMt4). On maximum flexion (LMt1), the means for the jungle boot and the Red Wing were significantly higher than the means for the remaining footwear types. There were no other significant findings on this measure. With regard to time to maximum flexion (LMt2), the three fastest times were for the jungle boot, the Reebok Pump, and the Nike cross trainer. These means did not differ from each other, but were significantly different from the means for the remaining three footwear types, which in turn did not differ from each other. On maximum flexion velocity (LMt3), the highest means were for the jungle boot, the Reebok Pump, and the Nike cross trainer. These means did not differ from each other, but were significantly different from the means for the remaining footwear types. No other significant findings were obtained on this parameter.

Rearfoot Movement (Tables F-13 and F-14)

The analyses of the rearfoot movement parameters did not reveal any significant interactions. However, there were significant main effects of footwear. Analyses of the male data yielded a significant main effect of footwear on three rearfoot movement parameters. For rearfoot angle at touchdown (LRf1), the highest mean, which was achieved with the Nike cross trainer, differed from all other means. No other significant findings were obtained on this parameter. On total rearfoot motion (LRf4), the lowest mean, which was obtained with the combat boot, was significantly different from the means for all other footwear types. This was the extent of the significant differences on the measure. For maximum rearfoot velocity (LRf5), a negative quantity, the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot yielded the highest absolute values. These values did not differ from each other, but were significantly different from the values for the remaining footwear types. The lowest absolute value was associated with the combat boot. This value differed significantly from the values for the remaining footwear types. No other differences were obtained on this measure.

Analyses of the female data yielded a significant effect of footwear only on maximum rearfoot angle (LRf2). The highest and the only positive value was for the combat boot. This value did not differ significantly from the values for the jungle boot, the Nike cross trainer, or the Red Wing work boot. However, the means for these footwear types did differ from the means for the remaining two footwear types. The lowest value was for the Rockport hiking boot. It differed significantly from all the means for all other footwear. No further differences were significant on this parameter.

EMG

Medial hamstring (Tables F-15 and F-16). Analyses of the medial hamstring data did not yield any significant footwear main effects, but there was one significant interaction involving footwear. It was an interaction between fitness and footwear that occurred in analysis of the male data for time to beginning of muscle activity (LEMG1), a negative parameter. The interaction means are presented graphically in Figure 49. The interaction appears to be attributable to the greater variation in footwear values for the medium fitness group compared with the other two fitness groups.

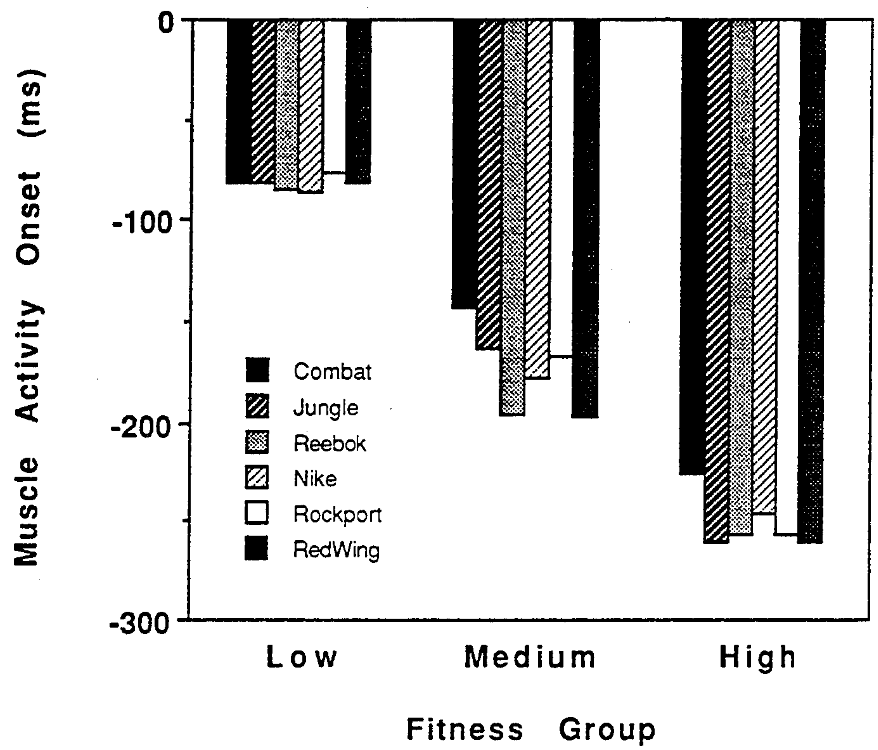

Figure 49. Means on time to onset of activity (LEMG1) of the medial hamstring during 0.32-m jump/landings under each footwear condition for men within each fitness group.

Rectus femoris (Table F-17 and F-18). There were no interactions involving footwear that were significant in the analyses of rectus femoris measures and only one footwear main effect was significant. This was found in analysis of the female data for time to termination of muscle activity (LEMG2). Here, the mean for the combat boot was significantly lower than the means for the remaining footwear types. No other differences on this parameter were significant.

Anterior tibialis (Tables F-19 and F-20). There was no significant main effect of footwear in the analyses of the anterior tibialis parameters and only one interaction involving footwear was significant. Analyses of the female data yielded a significant interaction between footwear and load on the time to onset of muscle activity (LEMG1), a negative quantity. The interaction, which is presented in Figure 50, appears to be attributable to the relatively low absolute value for the Reebok Pump under the no-load condition and its relatively high value under the 50-lb load.

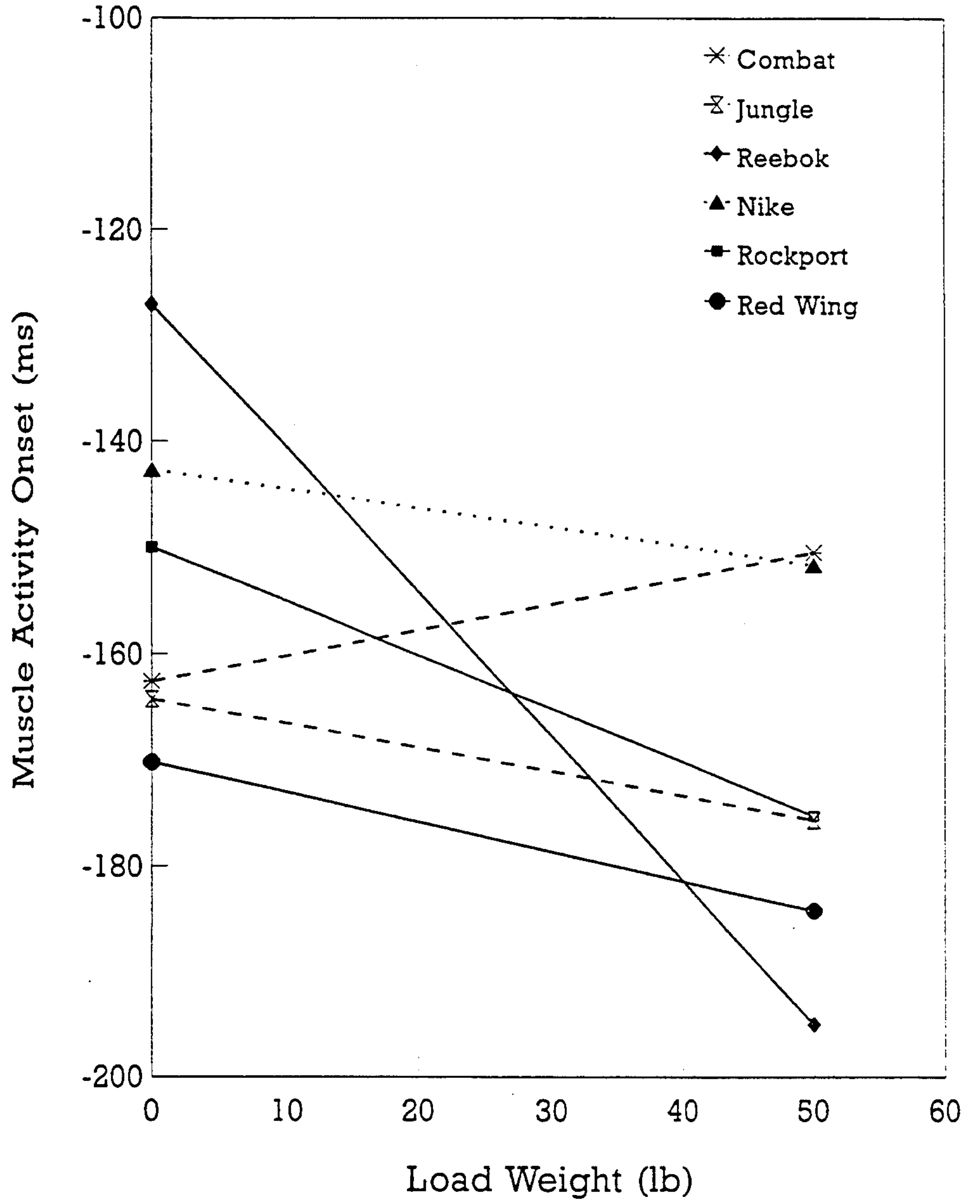

Figure 50. Means for women on time to onset of activity (LEMG1) of the anterior tibialis during 0.32-m jump/landings under each footwear and load condition.

Gastrocnemius/soleus (Tables F-21 and F-22). Analyses of these parameters did not yield any significant interactions nor any significant main effects involving footwear.

Results for Jump/Landings From 0.72 m

Summary

Interactions found to be significant in the analyses of the parameters for jump/landings from the 0.72-m height are indicated in Table 12. Unlike walking, marching, running, and jump/landings from 0.32 cm, jump/landings from 0.72 cm yielded significant second-order interactions. Three were found to be significant, all in analyses of the female data. The significant second-order interactions were obtained on maximum hip flexion (LH1), time to onset of activity of the medial hamstring muscle group (LEMG1), and time to termination of activity of the gastrocnemius/soleus muscle group (LEMG2).

Significant first-order interactions involving the footwear variable were obtained in analyses of both the male and the female data. In terms of interactions between fitness and footwear, significant findings were obtained for the male data in analyses of time to first maximum force (LFz2), slope of first maximum force (LFz3), time to maximum rearfoot angle (LRf3), and area under the curve for the gastrocnemius/soleus muscle group (LEMG3). The female data yielded significant interactions between fitness and footwear on first maximum force (LFz2), slope of first maximum force (LFz3), maximum dorsiflexion velocity (LA3), and maximum rearfoot velocity (LRf5).

Significant first-order interactions between footwear and load were also obtained in analyses of both the male and the female data. For the men, this interaction was significant on maximum flexion velocity at the metatarsals (LMt3). Analyses of the female data revealed significant interactions between footwear and load on maximum hip flexion (LH1) and time to termination of activity of the gastrocnemius/soleus muscle group (LEMG3).

A summary of the significance levels of the main effects for each of the jump/landing parameters is presented in Table 12. As indicated in the table, footwear had a significant main effect on a number of the measures captured during the 0.72-m jump/landings. However, there were again categories of measures in which none of the parameters was significantly affected by footwear. For the men, these were in-shoe pressure, the hip and the knee angle kinematics, rearfoot movement, and the activities of the four muscle groups. For the women, none of the parameters associated with in-shoe pressure, hip and knee angle kinematics, and the activities of the four muscle groups reflected a significant main effect of footwear.

Table 12. Significance of Main Effects and Summary of Significant Interactions in the Analyses of Jump/Landings From 0.72 m

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Vertical Ground Reaction Force Component			
LFz1	---	---	.001	.001	.001	---
LFz2	---[a]	---[a]	.001[a]	.001[a]	---	.005
LFz3	---[a]	---[a]	.001[a]	.001[a]	---	---
LFz4	---	---	---	.001	---	---
LFz5	---	---	---	.001	.001	.001
LFz6	---	---	.001	.001	---	---
			In-shoe Pressure			
LP1	---	---	---	---	---	---
LP2	---	---	---	---	---	---
LP3	---	---	---	---	---	---

Table 12. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Hip Angle			
LH1	---	---[d]	---	---[c,d]	---	---[c,d]
LH2	---	---	---	---	---	---
LH3	.001	---	---	---	---	---
LH4	---	---	---	---	---	---
			Sagittal Plane Kinematics - Knee Angle			
LK1	---	---[b]	---	---	.001	.001[b]
LK2	---	---	---	---	.01	.005
LK3	---	---	---	---	---	.01
LK4	---	---	---	---	---	---
			Sagittal Plane Kinematics - Ankle Angle			
LA1	---	---	.005	.001	---	---
LA2	---	---	---	---	---	.001
LA3	---	---[a]	.001	.001[a]	---	---
LA4	---	---	---	---	---	---

Table 12. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			Sagittal Plane Kinematics - Metatarsal Angle			
LMt1	---[b]	---	---	.001	---[b]	---
LMt2	---	---	.001	.001	---	---
LMt3	---	---	.001[c]	.001	---[c]	---
LMt4	---	---	---	---	---	---
			Rearfoot Movement			
LRf1	---	---	---	---	---	.005
LRf2	---	---	---	.001	---	---
LRf3	---[a]	---	---[a]	.001	---	---
LRf4	---	---	---	---	---	---
LRf5	.01	---[a]	---	.001[a]	---	---
			EMG - Medial Hamstring			
LEMG1	---	---[d]	---	---[d]	---	---[d]
LEMG2	---	---	---	---	---	---
LEMG3	---	---	---	---	---	---

Table 12. Continued

	Source of Variance					
	Fitness		Footwear		Load	
Parameter	Men	Women	Men	Women	Men	Women
			EMG - Rectus Femoris			
LEMG1	---	---	---	---	---	---
LEMG2	---	---	---	---	.005	.005
LEMG3	---[b]	---	---	---	.001[b]	---
			EMG - Anterior Tibialis			
LEMG1	---	---	---	---	---	---
LEMG2	---	---	---	---	.001	---
LEMG3	---	---	---	---	.01	---
			EMG - Gastrocnemius/Soleus			
LEMG1	---	---	---	---	---	---
LEMG2	---	---[d]	---	---[c,d]	---	---[c,d]
LEMG3	.001[a]	---	---[a]	---	---	---

Note. Dashes indicate a nonsignificant main effect.

[a]Significant Fitness x Footwear interaction. [b]Significant Fitness x Load interaction. [c]Significant Footwear x Load interaction. [d]Significant Fitness x Footwear x Load interaction.

Findings related to the footwear main effect are presented in Table 13 for the men and the women. Instances in which the footwear effect failed to reach significance are indicated. The results of the post-hoc, *HSD* procedure applied to each footwear effect that was significant are also included in the table. In the case of a significant effect, the footwear types with the highest and the lowest means, as determined by the *HSD* procedure, are indicated.

More detailed findings from the analyses of the jump/landings from 0.72 m are presented in Appendix G. The odd-numbered tables in the appendix contain the data for the men and the even-numbered tables contain the data for the women.

Vertical Ground Reaction Force Component (Tables G-1 and G-2)

Analyses of the vertical ground reaction force parameters did not yield significant second-order interactions or significant interactions between footwear and load. However, both the male and the female data revealed significant interactions between fitness and footwear on two parameters, time to first maximum force (LFz2) and slope of first maximum force (LFz3).

The male data for time to first maximum force (LFz2) are presented graphically in Figure 51. The largest mean in each fitness group was for the jungle boot, followed by the Reebok Pump. It appears that the significant interaction was attributable to variations over the fitness groups in the difference between these two means. The difference was greater in the high fitness group than in the other two fitness groups.

The other significant interaction between fitness and footwear obtained in the analyses of the male data, which occurred on the slope of first maximum force (LFz3) parameter, is presented graphically in Figure 52. This interaction appears to be due to the fact that the mean for the Reebok Pump was the lowest mean in the low and the medium fitness groups, whereas, in the high fitness group, the mean for the Reebok Pump was still among the lowest, but was essentially equal to the mean for the Nike cross trainer.

The female data for the significant interaction between fitness and footwear on time to first maximum force (LFz2) is presented in Figure 53. In all fitness groups, the jungle boot and the Red Wing work boot had the largest and the smallest means, respectively. The interaction appears to be due to the relationship among the means for the remaining footwear types. In both the low and the high fitness groups, the differences among these intermediate means were larger than they were in the medium fitness group.

Table 13. Extreme Values of Footwear Means Based on Post Hoc Analyses of Footwear Main Effect for Parameters of Jump/Landings From 0.72 m

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
		Vertical Ground Reaction Force Component		
LFz1	Ree, Nik, Roc	Com, Jun, Red	Ree, Nik	Com, Red
LFz2	Red	Jun, Ree	Red	Jun
LFz3	Ree, Nik	Red	Jun, Ree, Nik	Red
LFz4	---	---	Red	Jun, Ree
LFz5	---	---	Ree, Nik, Roc	Com, Jun, Red
LFz6	Red	Jun, Ree, Nik, Roc	Red	Jun, Ree, Nik, Roc
		In-shoe Pressure		
LP1	---	---	---	---
LP2	---	---	---	---
LP3	---	---	---	---
		Sagittal Plane Kinematics - Hip Angle		
LH1	---	---	---	---
LH2	---	---	---	---
LH3	---	---	---	---
LH4	---	---	---	---
		Sagittal Plane Kinematics - Knee Angle		
LK1	---	---	---	---
LK2	---	---	---	---
LK3	---	---	---	---
LK4	---	---	---	---

Table 13. Continued

	Men		Women	
Parameter	Lowest	Highest	Lowest	Highest
		Sagittal Plane Kinematics - Ankle Angle		
LA1[a]	Red	Com, Jun, Ree, Nik, Roc	Com, Jun, Red	Ree
LA2	---	---	---	---
LA3[a]	Com, Jun, Red	Nik, Roc	Com, Red	Jun, Ree, Nik, Roc
LA4	---	---	---	---
		Sagittal Plane Kinematics - Metatarsal Angle		
LMt1	---	---	Com, Ree, Nik, Roc	Jun, Red
LMt2	Nik, Roc	Com, Red	Jun, Nik	Com
LMt3	Red	Jun, Nik	Com, Roc, Red	Jun, Ree, Nik
LMt4	---	---	---	---
		Rearfoot Movement		
LRf1	---	---	---	---
LRf2[a]	---	---	Com, Jun, Nik, Red	Ree, Roc
LRf3	---	---	Com, Nik, Roc	Jun, Ree, Red
LRf4	---	---	---	---
LRf5[a]	---	---	Com, Ree, Red	Jun, Roc
		EMG - Medial Hamstring		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---

Table 13. Continued

Parameter	Men Lowest	Men Highest	Women Lowest	Women Highest
		EMG - Rectus Femoris		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---
		EMG - Anterior Tibialis		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---
		EMG - Gastrocnemius/Soleus		
LEMG1	---	---	---	---
LEMG2	---	---	---	---
LEMG3	---	---	---	---

Note. Dashes indicate a significance level of $p > .05$. Com = combat boot; Jun = jungle boot; Ree = Reebok Pump; Nik = Nike cross trainer; Roc = Rockport hiking boot; Red = Red Wing work boot.

[a]Values are highest and lowest absolute values.

The other significant interaction between fitness and footwear obtained in the analyses of the female data, which occurred on the slope of first maximum force (LFz3) parameter, is presented graphically in Figure 54. The highest mean in all fitness groups was for the Red Wing work boot. In the low and the high fitness groups, the next highest mean was for the combat boot. However, in the medium fitness group, the second highest mean was for the Rockport hiking boot.

With regard to footwear main effects, the male data yielded a significant finding on all parameters, except impact ratio (LFz4) and second maximum force (LFz5). On first maximum force (LFz1), the three highest values did not differ from each other, but were significantly different from the remaining values. The combat and the jungle boots, along with the Red Wing, yielded the three highest values. There were no other

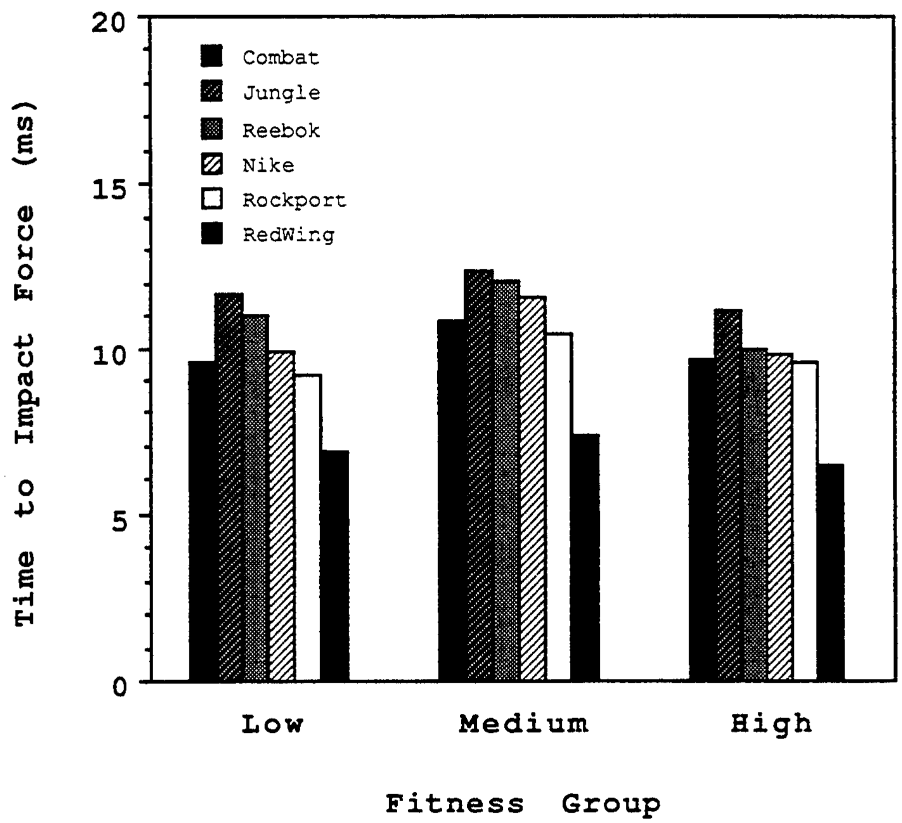

Figure 51. Means on time to first maximum force (LFz2), a vertical ground reaction force component, during 0.72-m jump/landings under each footwear condition for men within each fitness group.

significant differences on this parameter. For time to first maximum force (LFz2), the value for the Red Wing was significantly lower than the values for the other footwear types. The value for the jungle boot was significantly higher than all other values except that for the Reebok Pump. This was the extent of the significant differences on the parameter. On the slope of the first maximum force (LFz3), the value for the Red Wing was significantly higher than the values for all footwear types except the combat boot. The values for the Reebok Pump and the Nike cross trainer were significantly lower than the values for all footwear except the jungle boot and the Rockport hiking boot. No other significant findings were obtained on this measure. For time to second maximum force (LFz6), the mean for the Red Wing was significantly lower than all other means, except that for the combat boot. No other differences were significant on this measure.

The female data yielded significant effects of footwear on all vertical force parameters. The highest values for first maximum force (LFz1) were achieved with the

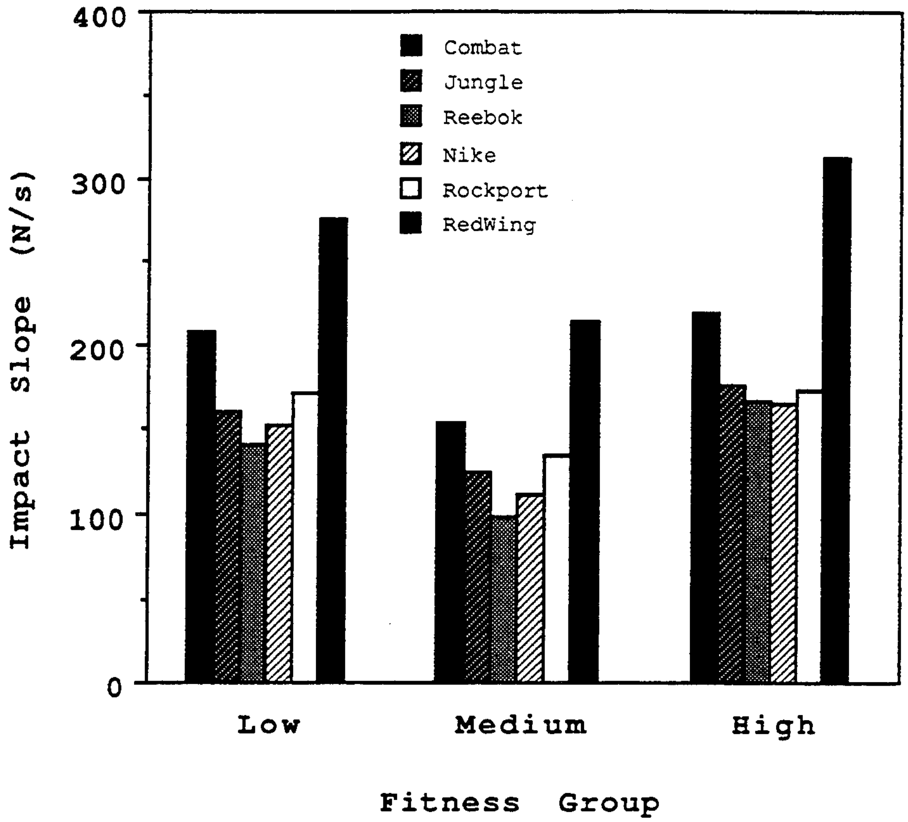

Figure 52. Means on slope of first maximum force (LFz3), a vertical ground reaction force component, during 0.72-m jump/landings under each footwear condition for men within each fitness group.

combat boot and the Red Wing. These values were significantly different from the lowest values, which were achieved with the Reebok Pump and the Nike cross trainer. No other significant differences were obtained on this measure. The shortest times to first maximum force (LFz2) were associated with the Red Wing. These times differed significantly from all others. The next shortest times were for the combat boot and the Rockport hiking boot. These times differed significantly from the times for all other footwear types except the Nike cross trainer. The longest times were achieved with the jungle boot. These times differed from all others except that for the Reebok Pump. On the slope of the first maximum force (LFz3), the mean for the Red Wing was significantly higher than the means for the other footwear types. The means for the jungle boot, the Reebok Pump, and the Nike cross trainer were significantly lower than the means for all other footwear. No further significant findings were obtained on this measure.

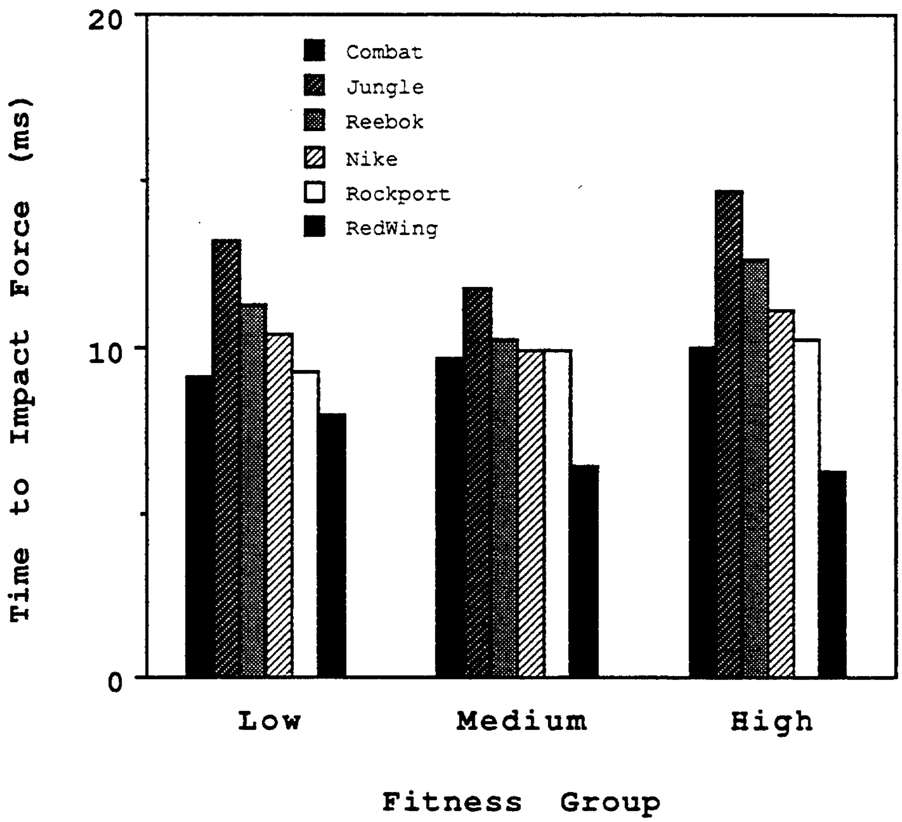

Figure 53. Means on time to first maximum force (LFz2), a vertical ground reaction force component, during 0.72-m jump/landings under each footwear condition for women within each fitness group.

With regard to the female data for impact ratio (LFz4), the lowest mean, that for the Red Wing work boot, was significantly different from the means for the other footwear types. The next lowest mean was associated with the combat boot, and this mean, as well, differed significantly from all others. The highest means were for the jungle boot and the Reebok Pump. The means for these two footwear conditions did not differ from each other, but they did differ significantly from the means for the other footwear. No further differences were obtained on this parameter. With regard to second maximum force (LFz5), the three highest values did not differ from each other, but did differ significantly from the remaining values. The three highest values were achieved with the combat boot, the jungle boot, and the Red Wing. No other significant findings were obtained on this measure. For time to second maximum force (LFz6), the value for the Red Wing was significantly lower than the values for the other footwear

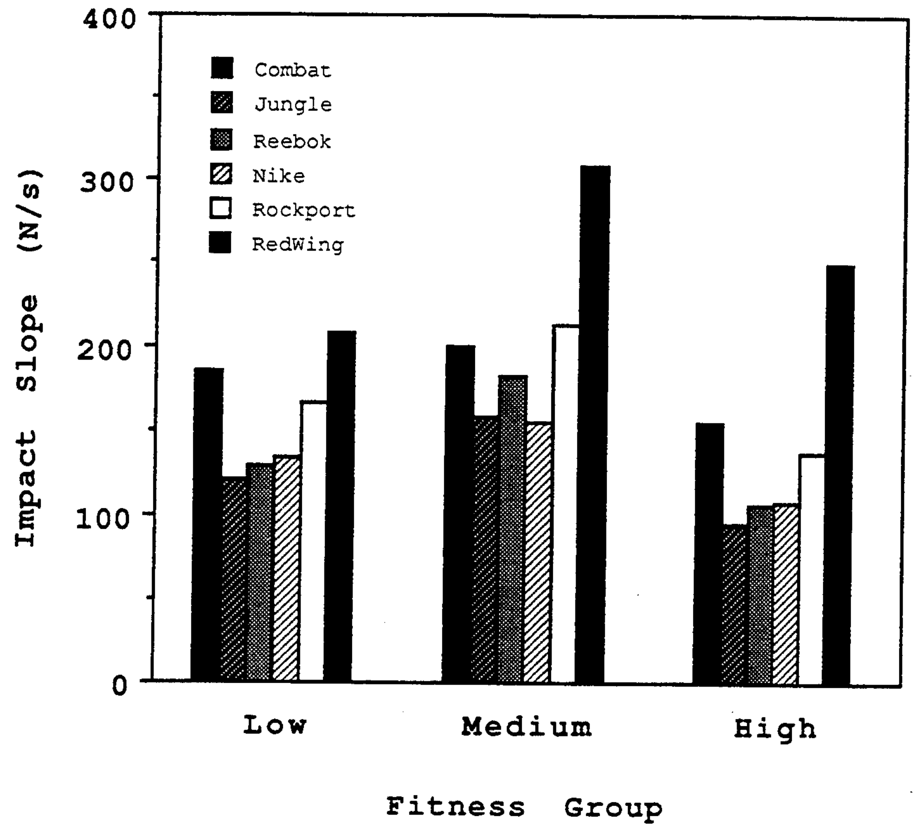

Figure 54. Means on slope of first maximum force (LFz3), a vertical ground reaction force component, during 0.72-m jump/landings under each footwear condition for women within each fitness group.

types. The next lowest value was achieved with the combat boot. This also differed significantly from the values for the other footwear types. No other significant differences were obtained on this measure.

In-shoe Pressure (Tables G-3 and G-4)

Neither the male nor the female data yielded significant findings on this measure.

Sagittal Plane Kinematics

Hip angle (Tables G-5 and G-6). Neither the male nor the female data revealed a significant main effect of footwear on the hip angle parameters. Furthermore, analysis of the male data for hip angle did not reveal any significant interactions involving footwear. However, analysis of the female data did. There was a significant second-order interaction on maximum flexion (LH1), as well as a significant first-order interaction on this same parameter.

The means associated with the second-order interaction on maximum flexion (LH1) are presented graphically in Figure 55. The interaction appears to be due to differences among the fitness group-load combinations in the footwear type with the highest mean. For example, in the low fitness group, the combat boot had the highest mean under the no-load conditions and the Red Wing work boot had the highest mean under the 50-lb load condition.

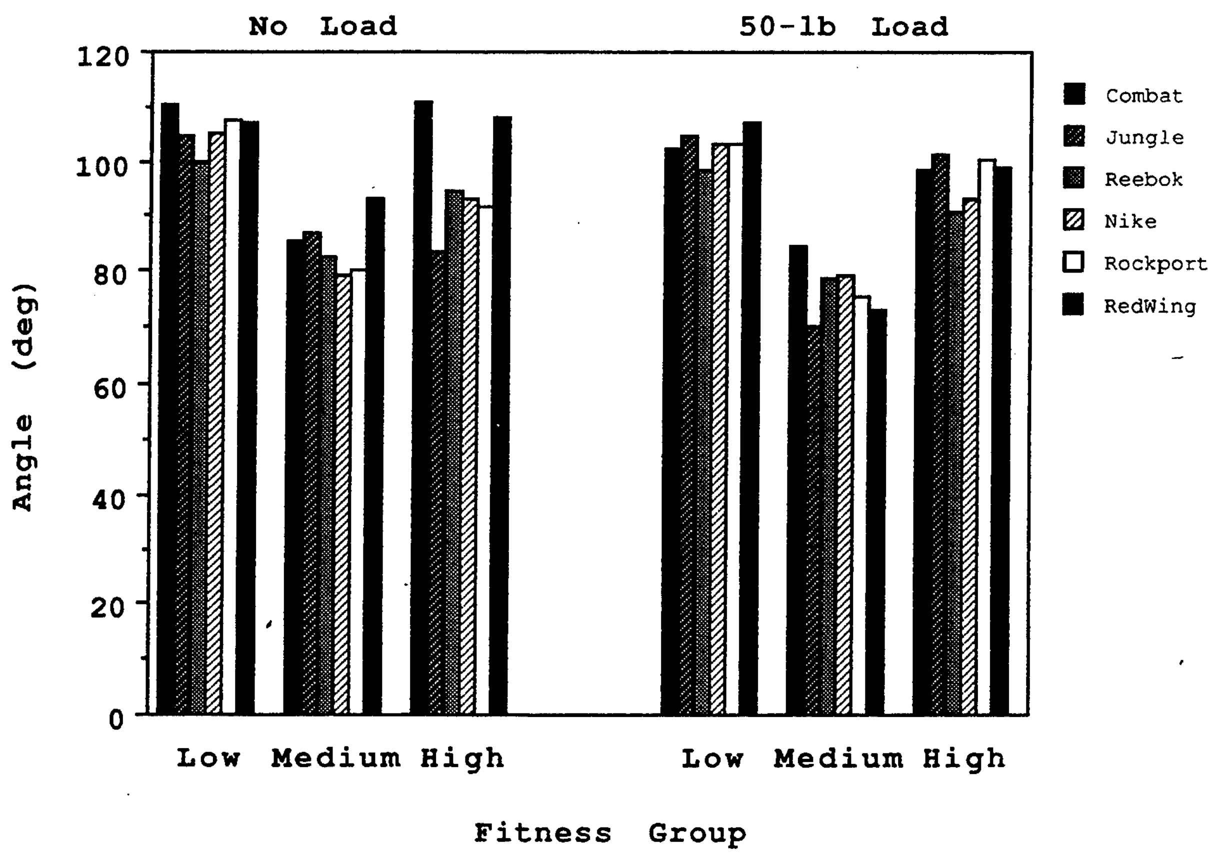

Figure 55. Means on maximum hip flexion (LH1) during 0.72-m jump/landings under each footwear and load condition for women within each fitness group.

The footwear by load interaction found to be significant in analysis of the female data for maximum flexion (LH1) is presented in Figure 56. The interaction appears to be attributable to the fact that the means for the combat boot and the Red Wing work boot decreased substantially as load was increased from 0 lb to 50 lb, whereas the means for the other footwear types either rose or decreased to a lesser extent.

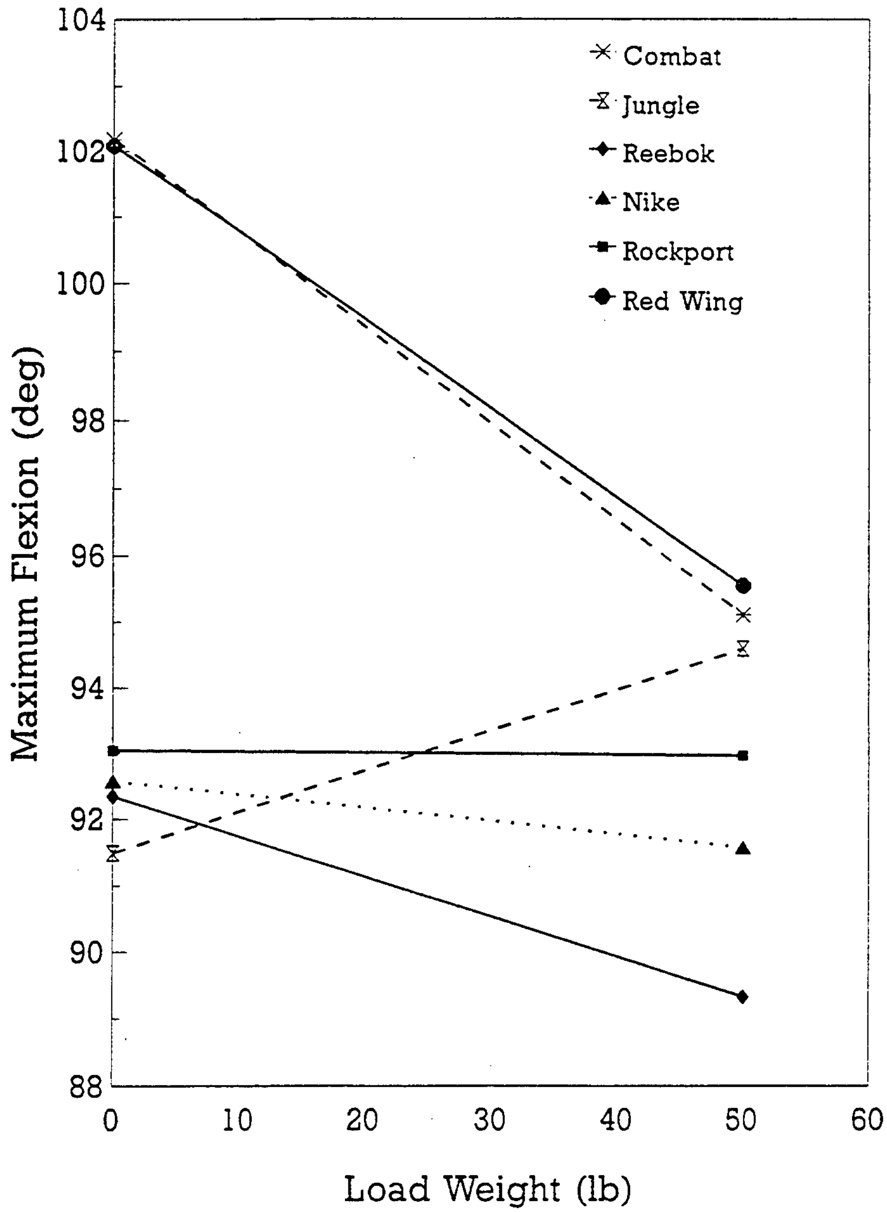

Figure 56. Means for women on maximum hip flexion (LH1) during 0.72-m jump/landings under each footwear and load condition.

Knee angle (Tables G-7 and G-8). There were no significant interactions involving footwear or significant main effects of footwear in the analyses of the knee angle parameters.

Ankle angle (Tables G-9 and G-10). The ankle angle parameters revealed one significant interaction involving the footwear variable. This was an interaction between fitness and footwear in the analysis of the female data for maximum dorsiflexion velocity (LA3). The means for this interaction are presented graphically in Figure 57. The interaction appears to be attributable to the fact that there were greater differences among the footwear means in the high fitness group compared with the other two fitness groups.

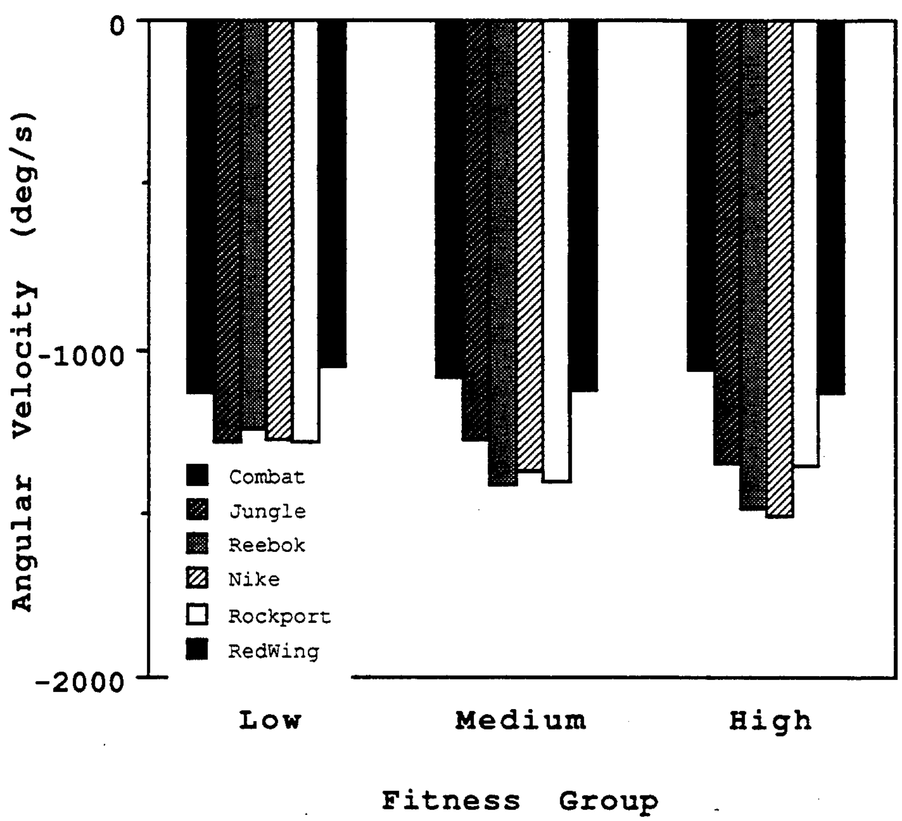

Figure 57. Means on maximum ankle dorsiflexion velocity (LA3) during 0.72-m jump/landings under each footwear condition for women within each fitness group.

In terms of the main effect of footwear on ankle angle parameters, analyses of the male data revealed significant findings on two measures. One was maximum dorsiflexion (LA1) and the other was maximum dorsiflexion velocity (LA3). For maximum dorsiflexion (LA1), a negative quantity, the lowest absolute value, which was achieved with the Red Wing, differed significantly from the values for the other footwear types. No further significant findings were obtained on this measure. For maximum dorsiflexion velocity (LA3), another negative measure, the highest absolute values were achieved with the Nike cross trainer and the Rockport hiking boot. These values did not differ from each other, but were significantly different from the values for all the remaining footwear types except the Reebok Pump. There were no other significant differences on this measure.

Analyses of the female data revealed a significant main effect of footwear on the same two parameters found to be significant in analyses of the male data, maximum dorsiflexion (LA1) and maximum dorsiflexion velocity (LA3). The highest absolute value for maximum dorsiflexion (LA1) was associated with the Reebok Pump. This value differed significantly from the three lowest absolute values, which were for the combat boot, the jungle boot, and the Red Wing. No other significant findings were obtained on this measure. For maximum dorsiflexion velocity (LA3), the two lowest absolute values, those for the combat boot and the Red Wing, did not differ from each other. However, they were significantly different from the absolute values for the remaining footwear types. No other findings for this measure were significant.

Metatarsal angle (Tables G-11 and G-12). There was one significant interaction involving footwear in the analyses of the metatarsal angle parameters. It was the interaction between footwear and load in the analysis of the male data for maximum flexion velocity (LMt3). The interaction means are presented in Figure 58. It appears that the interaction is ascribable to the fact that the means for the Reebok Pump and the Rockport hiking boot decreased as load was increased from 0 lb to 50 lb, whereas the means for the other footwear types increased with the increase in load weight. Furthermore, the relationship between the means for the 50-lb and the 70-lb loads varied across footwear types. For some footwear types, the means changed little with changes in load; for others the means increased or decreased substantially.

In terms of footwear main effects, two parameters were found to be significant in the analyses of the male data. These were time to maximum flexion (LMt2) and maximum flexion velocity (LMt3). With regard to time to maximum flexion (LMt2), the highest values were obtained with the combat boot and the Red Wing. These means did not differ from each other, but did differ significantly from the means for the remaining footwear types. The lowest values, those for the Nike cross trainer and the Rockport hiking boot, also did not differ significantly from each other, but were different from the means for the other footwear types. No further significant differences were obtained on this measure. On the maximum flexion velocity parameter (LMt3), the mean for the Red Wing was significantly lower than all other means and the means for the jungle boot and the Nike cross trainer were significantly higher than all other means. This was the extent of the significant findings for the parameter.

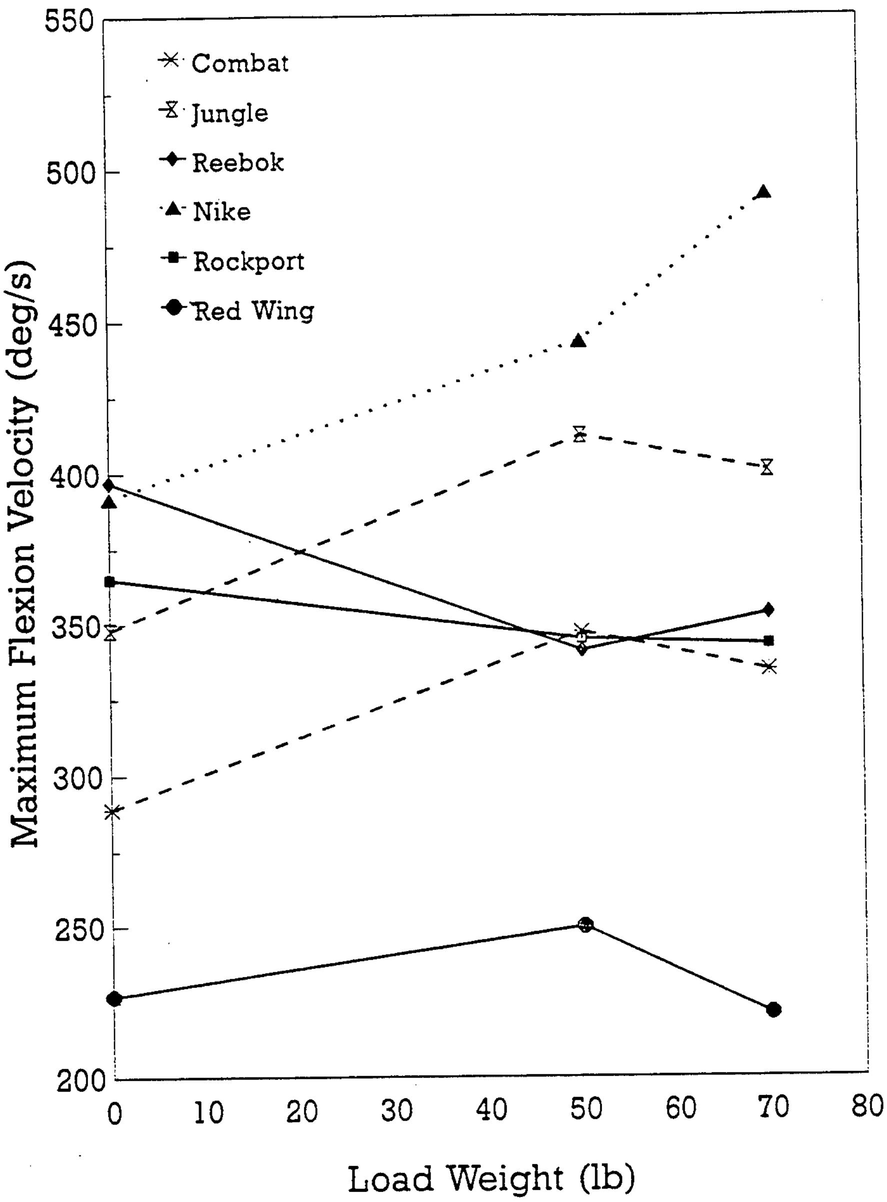

Figure 58. Means for men on maximum metatarsal flexion velocity (LMt3) during 0.72-m jump/landings under each footwear and load condition.

The analyses performed on the female data yielded significant footwear effects on all parameters, except time to maximum flexion velocity (LMt4). For maximum flexion (LMt1), the means for the jungle boot and the Red Wing were significantly higher than the means for the remaining footwear conditions. There were no other significant findings on this measure. With regard to time to maximum flexion (LMt2), the mean for the combat boot was significantly higher than the means for the other footwear items. The lowest means, those for the jungle boot and the Nike cross trainer, did not differ from each other, but were significantly different from the means for the remaining footwear types. There were no further significant findings on this measure. On maximum flexion velocity (LMt3), the highest values were associated with the jungle boot, the Reebok Pump, and the Nike cross trainer. These means did not differ from each other, but were significantly different from the means for the remaining footwear types. No other significant findings were obtained on this measure.

Rearfoot Movement (Tables G-13 and G-14)

The analyses of the rearfoot movement parameters revealed two significant interactions involving footwear, one in the male and one in the female data. Both were interactions between fitness and footwear. For the men, this interaction occurred on the measure of time to maximum rearfoot angle (LRf3). For the women, the significant interaction between fitness and footwear occurred on maximum rearfoot velocity (LRf5).

The significant interaction between fitness and footwear found in the analyses of the male data is presented in Figure 59. The interaction appears to be attributable to the larger differences among footwear means in the medium and the high fitness groups compared with the low fitness group.

The interaction between fitness and footwear found to be significant in the analyses of the female data for maximum rearfoot velocity (LRf5), a negative parameter, is presented in Figure 60. The interaction appears to be attributable to the fact that the largest absolute values in the medium and the high fitness groups were achieved with the Rockport hiking boot, whereas the largest absolute value in the low fitness group was for the jungle boot.

Analyses of the male data did not yield any significant main effects of footwear. Analyses of the female data yielded a significant effect of footwear on three parameters. For maximum rearfoot angle (LRf2), a negative quantity, the absolute values for the Reebok Pump and the Rockport hiking boot did not differ from each other, but they were significantly larger than the means for the remaining footwear types. No other findings on this measure were significant. For time to maximum rearfoot angle (LRf3), the mean times for the jungle boot, the Reebok Pump, and the Red Wing did not differ from each other, but were significantly slower than the means for the remaining footwear types. No other findings on this measure were significant. For maximum rearfoot velocity (LRf5), a negative quantity, the two largest absolute values were achieved with the jungle boot and the Rockport hiking boot. These values did not differ from each other, but were significantly different from the three smallest absolute values. The smallest values were associated with the combat boot, the Reebok Pump, and the Red Wing. No other significant findings were obtained on this parameter.

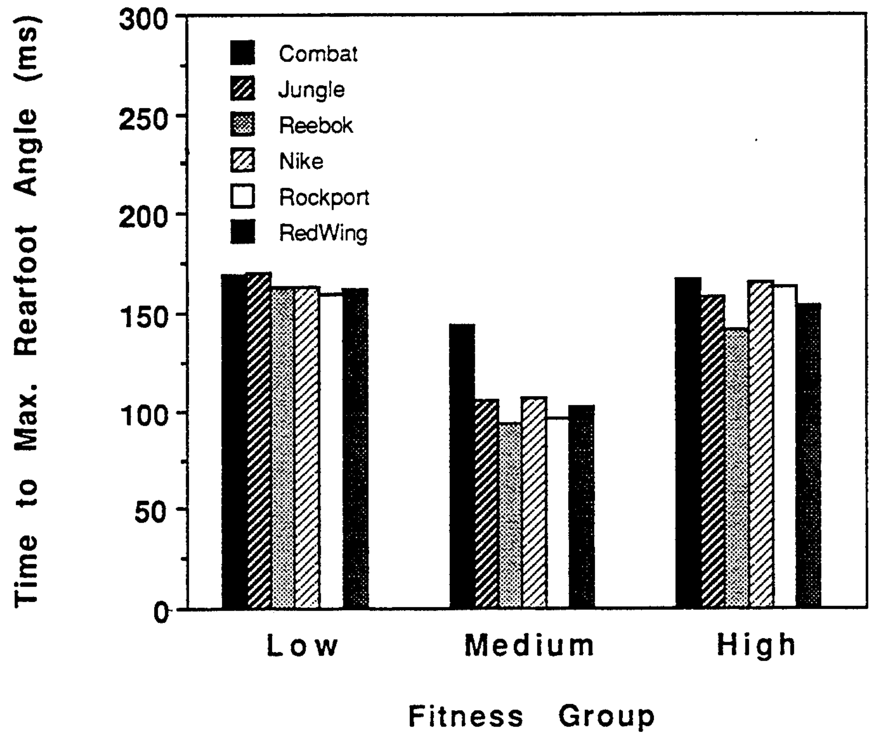

Figure 59. Means on time to maximum rearfoot angle (LRf3) during 0.72-m jump/landings under each footwear condition for men within each fitness group.

EMG

Medial hamstring (Tables G-15 and G-16). Analyses of the medial hamstring data did not yield any significant footwear main effects, but there was one significant interaction involving footwear. This was a second-order interaction found in analysis of the female data for time to beginning of muscle activity (LEMG1), a negative quantity.

The means associated with the second-order interaction on time to beginning of muscle activity (LEMG1) are presented in Figure 61. The interaction appears to be due to differences among the fitness group-load combinations in the footwear type with the highest mean. For example, in the high fitness group, the Red Wing work boot had the highest absolute value under the no-load condition and the combat boot had the highest absolute value under the 50-lb load condition.

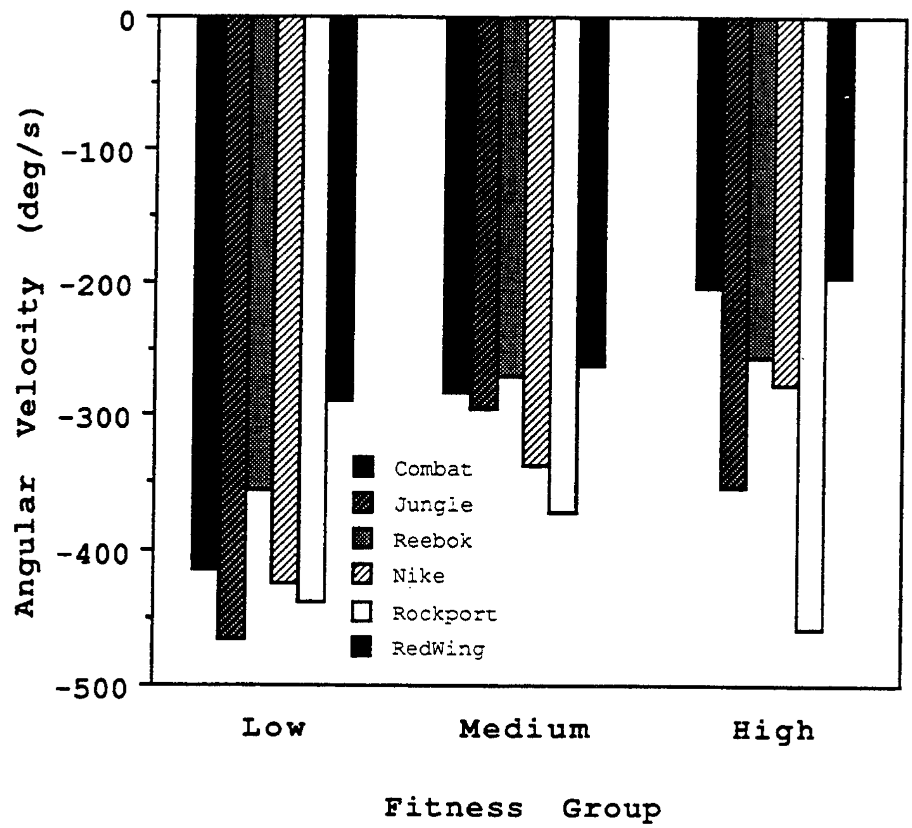

Figure 60. Means on maximum rearfoot velocity (LRf5) during 0.72-m jump/landings under each footwear condition for women within each fitness group.

Rectus femoris (Tables G-17 and G-18). Analysis of the rectus femoris parameters did not yield any significant interactions involving footwear nor any significant main effects of footwear.

Anterior tibialis (Tables G-19 and G-20). Analysis of the anterior tibialis parameters did not yield any significant interactions nor any significant main effects of footwear.

Gastrocnemius/soleus (Tables G-21 and G-22). Analyses of these parameters did not reveal any significant main effects of footwear However, there were significant interactions involving footwear.

For the men, fitness interacted significantly with footwear on area under the curve (LEMG3). The significant interaction is presented in Figure 62. It appears that the

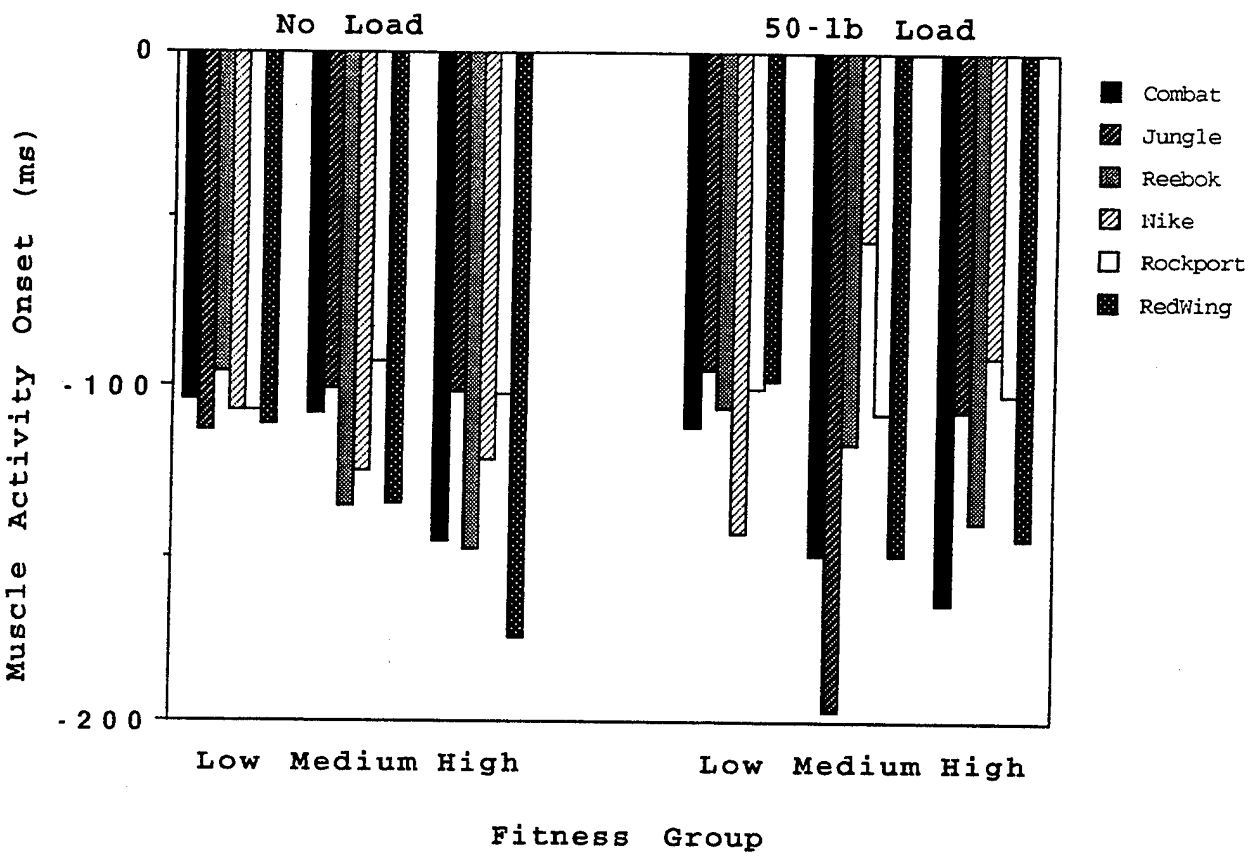

Figure 61. Means on time to onset of activity (LEMG1) of the medial hamstring during 0.72-m jump/landings under each footwear and load condition for women within each fitness group.

interaction was due to the fact that the largest mean in the low fitness group was for the Red Wing work boot, whereas the largest mean in the other two fitness groups was for the Reebok Pump.

The female data revealed a significant second-order interaction on time to termination of muscle activity (LEMG2). The interaction is presented graphically in Figure 63. As was the case with the significant second-order interactions presented previously, this interaction appears to be due to differences among the fitness group-load combinations in the footwear type with the highest mean. For example, in the high fitness group, the Reebok Pump had the highest value under the no-load condition, whereas the Red Wing work boot had the highest value under the 50-lb load condition.

The female data also yielded a significant first-order interaction between footwear and load on time to termination of muscle activity (LEMG2). The interaction is

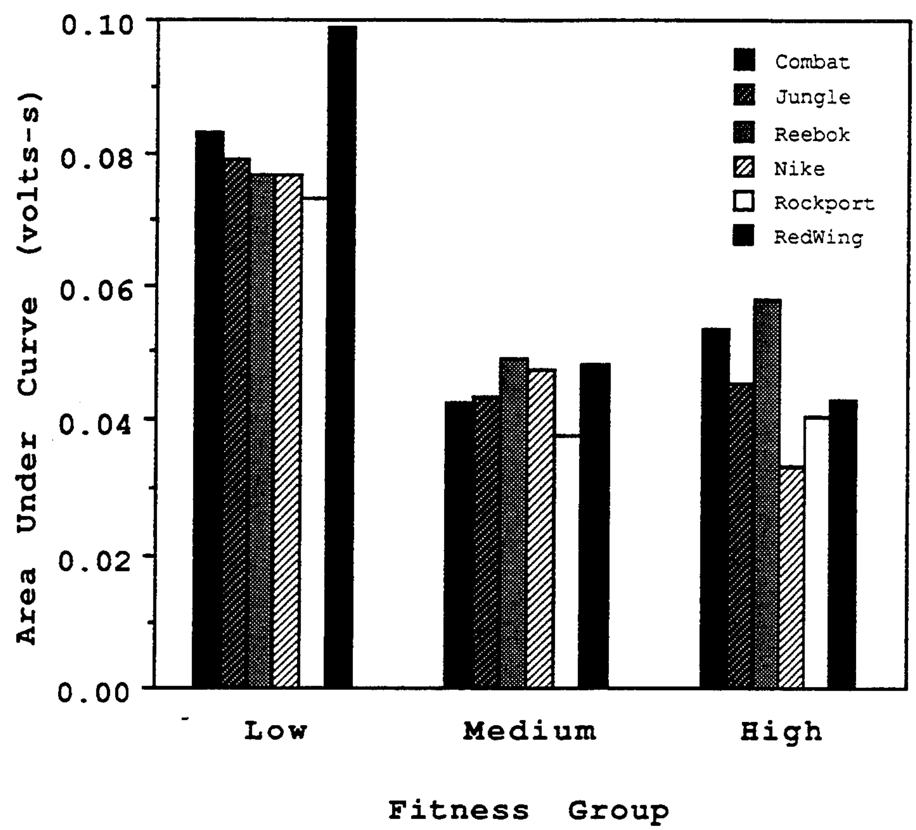

Figure 62. Means on area under the curve (LEMG3) for the gastrocnemius/soleus during 0.72-m jump/landings under each footwear condition for men within each fitness group.

presented graphically in Figure 64. This finding appears to be attributable to the fact that the Red Wing had a relatively low mean under the no-load condition and a relatively high mean under the 50-lb load condition.

Discussion

In a study of the kinetic and kinematic characteristics of jump landings from 0.32 m, 0.72 m, and 1.28 m, McNitt-Gray (1991) reported that peak vertical impact forces increased significantly with increases in the impact velocities associated with increases in jump height. In the present study also, first maximum vertical forces at the 0.72-m height were higher than those at the 0.32-m height. However, in terms of relative force magnitudes for the various footwear items, the results on the first maximum vertical force variable were quite similar at both jump heights and for both genders. The forces of the largest magnitude were associated with the military boots and the Red Wing

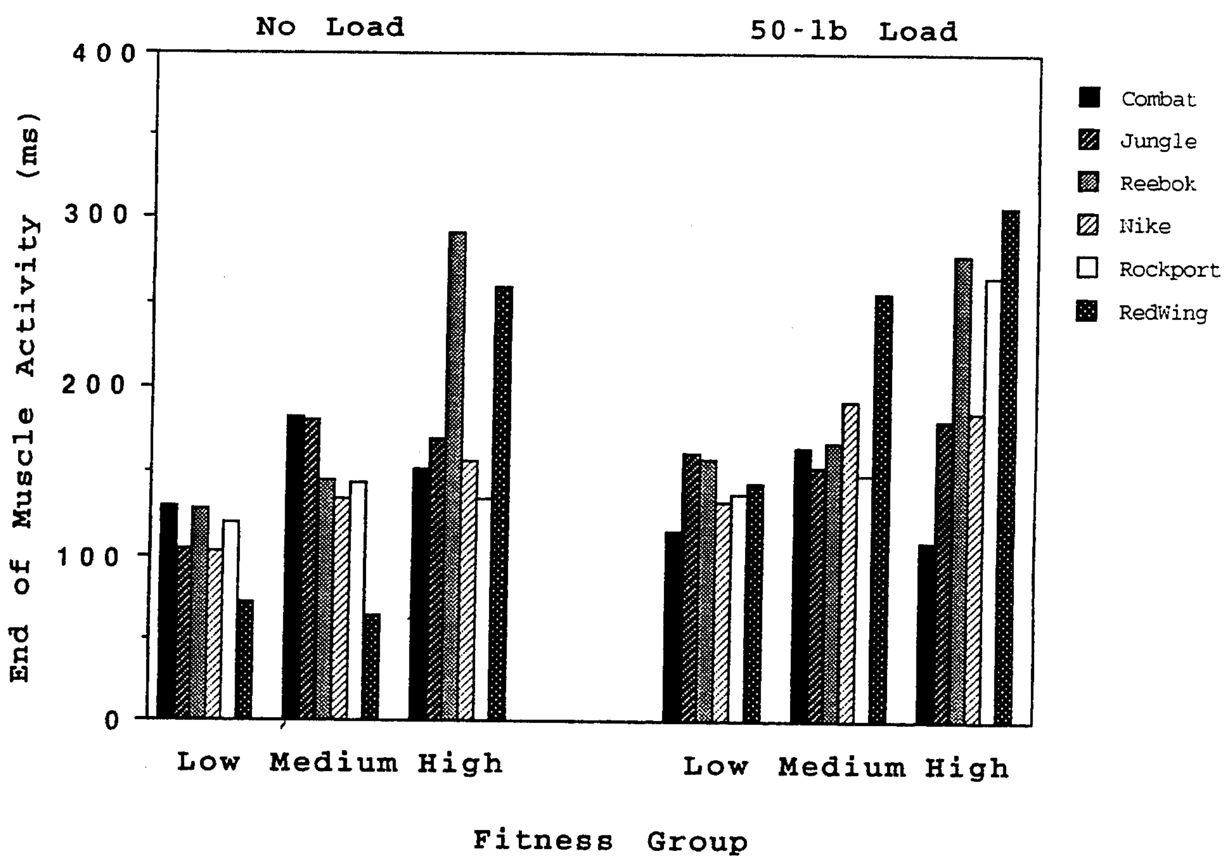

Figure 63. Means on time to termination of activity (LEMG2) of the gastrocnemius/soleus during 0.72-m jump/landings under each footwear and load condition for women within each fitness group.

work boot and the values for these three footwear types did not differ significantly. The smallest magnitude forces occurred with the Reebok Pump and the Nike cross trainer and the values for these footwear types did not differ significantly.

Although the findings were consistent with regard to footwear items resulting in the largest and the smallest magnitudes of first maximum vertical force, there were differences between the 0.32 m and the 0.72 m jump heights, and between the male and the female data sets, in the extent to which the force magnitudes with the combat and the jungle boots exceeded those with the Reebok Pump and the Nike cross trainer. For the male data at the lower height, the force amplitudes with the military boots did not differ significantly from those with the Reebok Pump or the Nike cross trainer, whereas, at the 0.72-m height, the amplitudes with the military boots did differ significantly from those with the other two footwear types. For the female data at the 0.32-m height, the force

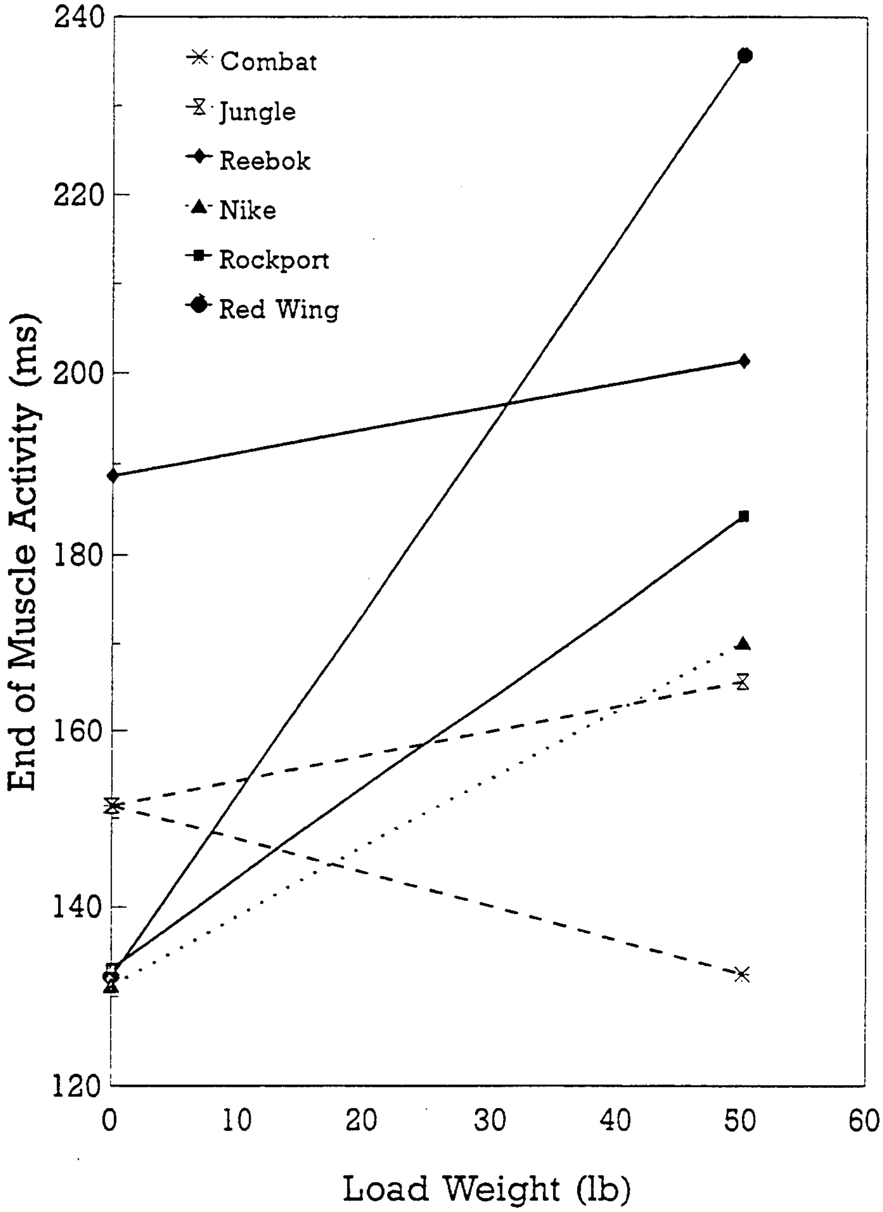

Figure 64. Means for women on time to termination of activity (LEMG2) of the gastrocnemius/soleus during 0.72-m jump/landings under each footwear and load condition.

amplitude with the jungle boot did not differ from that with the other footwear types, but the amplitude with the combat boot differed significantly from the lowest amplitude, that with the Nike cross trainer. At the higher height, the female score for the jungle boot again did not differ from the scores for the other footwear types, but the score for the combat boot differed significantly from those for both the Reebok Pump and the Nike cross trainer.

These results for the first maximum vertical forces during the 0.32-m and the 0.72-m jump landings are not unlike the results obtained during the locomotor activities of walking and marching. On each task, the first maximum vertical forces associated with the combat and the jungle boots, although relatively high, did not consistently differ significantly from the forces with the Nike cross trainer, in spite of the fact that a substantial difference would be expected on the basis of the peak g values obtained in the materials testing phase (Hamill and Bensel, 1992). However, the data for second maximum vertical forces during the jump landings did, with one exception, yield force magnitudes with the military boots that were significantly higher than those for the Nike cross trainer. The exception was the male data during the jump from the 0.72-m height. Here, the second maximum vertical forces of the largest magnitude were those for the combat and the jungle boots, but the magnitudes did not differ significantly from those for the Nike cross trainer, or for the other footwear types.

As was the case for the locomotor movements, the times to first maximum vertical force for the jump landings reflected to only a limited extent the finding from the materials testing of the footwear impact properties that the shortest times to peak g were associated with the military boots. The male and the female data for the jump landings from both heights yielded a significant effect of footwear on time to first maximum vertical force. The shortest times were recorded when the Red Wing work boot was being worn, and the times for the combat boot were also relatively short. Most noteworthy is the fact that the longest times to first maximum force occurred when the jungle boot was being used. In the female data set for the 0.32-m jump and in the male and the female data sets for the 0.72-m jump, the times for the jungle boot were even significantly longer than those for the Nike cross trainer. Both the male and the female data revealed a significant interaction between fitness group and footwear type on time to first maximum force in the 0.72-m jump. However, regardless of fitness group, the longest times were associated with the jungle boot.

The results for the jungle boot on times to second maximum vertical force were somewhat more compatible with the materials testing findings than the results for times to first maximum force were insofar as the jungle boots did not yield the longest times to second maximum force. For the male data on the 0.32-m jump/landing, a significant footwear effect was not obtained. However, the female data for the 0.32-m jump yielded a significant effect, and the longest times were for the Red Wing work boot, followed by the military boots. The values for these three footwear types did not differ from each other, but they did differ significantly from the values for the remaining footwear types.

With regard to the 0.72-m jump/landings, a significant effect of footwear on time to second maximum force was obtained in the analyses of the male and the female data sets. For both genders, the shortest times to second maximum force occurred with the Red Wing work boot, followed by the combat boot. In the case of the male data, the values for the combat and the jungle boots did not differ significantly from the highest value, that for the Rockport hiking boot. In the case of the female data, the value for the combat boot did differ from the highest value, that for the Reebok Pump, whereas the value for the jungle boot did not.

Like the results for the locomotor movements, the times to first and to second maximum force during the jump/landings did not consistently reflect the shorter times that would be expected with the military boots based upon the materials testing of footwear impact properties (Hamill and Bensel, 1992). The jump/landing data for peak heel and peak forefoot pressure did not yield significant footwear effects. Thus, these data, as well, failed to reflect findings from the materials testing. In addition, the jump/landing data did not reveal a significant effect of footwear on the amplitude of the signals from any of the four muscle groups being recorded. However, the military boots were associated with relatively high magnitudes of first and of second maximum vertical force at both jump heights, a finding that is compatible with the impact characteristics of the footwear established during the materials testing.

There was no evidence in the knee angle data for the jump/landings that the body compensated for the relatively large amplitudes of the vertical forces experienced with the military boots. The analyses of maximum knee flexion revealed only one significant effect, an interaction between footwear and load for the female data at the 0.32-m height. The significant finding is unrelated to the military boots, rather it is attributable to the fact that the Rockport hiking boot yielded the smallest flexion angles under the no-load condition and the largest under the 50-lb load condition. Furthermore, the jump/landing data did not yield significant effects of footwear on the knee flexion velocity measure. Footwear did, however, significantly influence some ankle joint parameters.

McNitt-Gray (1991) analyzed sagittal plane kinematics in her study of jump/landings from three heights. She found that, at touchdown, the initiation of the landing phase, the ankle joint, as well as the hip and the knee joints, are in an extended position. McNitt-Gray (1991) maintained that this posture provides the potential for the body to use joint range of motion during the landing phase to minimize the load on the skeletal system. The uppers of the footwear items used in the present study differed in height, suggesting the possibility that some items may have restricted ankle dorsiflexion during the landing phase to a greater extent than others, with the result being a more substantial load on the body. The combat boot had the highest uppers, followed by the jungle boot and then the Red Wing work boot; the Nike cross trainer had the lowest uppers.

In the analysis of the locomotor movements, it was found that maximum ankle dorsiflexion did not vary in an ordered fashion with the height of the footwear upper. However, the three smallest dorsiflexion angles, denoting the least amount of flexion about the ankle joint, were generally associated with the military boots and the Red Wing work boot, the three footwear items with the highest uppers. On the 0.32-m jump/landings, analysis of the male data did not yield a significant footwear effect, but analysis of the female data did. Here, the smallest dorsiflexion angles, which were associated with the jungle boot and the Red Wing work boot, differed significantly from the angles for the other footwear types, including the combat boot. On the 0.72-m jump/landings, both the male and the female data yielded a significant footwear effect on maximum dorsiflexion. For the men, the smallest angle was achieved with the Red Wing work boot and its value differed significantly from the values for the other footwear types. For the women, the military boots and the Red Wing work boot yielded the smallest angles, and their values differed significantly from the largest angle, which was associated with the Reebok Pump.

These findings for the maximum ankle dorsiflexion measure on the jump/landings are similar to the findings obtained for the measure on the locomotor activities insofar as the amount of flexion did not vary directly as a function of upper height. However, the military boots and the Red Wing work boot were again associated with less flexion at the ankle joint, and, thus, possibly a more substantial load on the body, compared with some of the other footwear items.

Maximum dorsiflexion velocities during landing were also differentially affected by footwear type. At both jump heights, both the male and the female data sets revealed smaller negative peak joint velocities with the military boots and the Red Wing work boot than with the other footwear types. This finding is at odds with the results of the locomotor activities, where the military boots and the Red Wing work boot were associated with the largest magnitude ankle joint velocities.

The metatarsal extension data for the locomotor movements revealed a greater range of motion at the joint with the military boots and the Red Wing work boot than with some of the other footwear. This result is only partially supported by the jump/landing findings. For both the 0.32-m and the 0.72-m jump heights, the female data yielded a significant effect of footwear on maximum metatarsal flexion, but the male data did not. In the female data set, the largest angles, indicating the greatest angular displacement at the metatarsal joint, were associated with the Red Wing work boot, followed by the jungle boot. The values for these footwear types did not differ significantly from each other, but they did differ from the values for all other footwear, including the combat boot.

During the locomotor activities, the velocities of the movement at the metatarsal joint were relatively high when the military boots were used. For the jump/landings, this was the case only with regard to the jungle boot. At both jump heights and for both the male and the female data sets, the combat boot, along with the Red Wing work boot, had flexion velocities that were significantly lower than those for all other footwear types.

The data collected during the locomotor activities related to rearfoot movement parameters provided some support to the finding from the materials testing that the military boots and the Red Wing work boot are highly stable compared with the other footwear items studied (Hamill and Bensel, 1992). The data collected during the jump/landings did as well. The male data did not yield a significant effect of footwear on the maximum rearfoot angle measure at either jump height. However, the female data yielded a significant effect at both jump heights and the angles associated with the military boots were among the smallest. Total rearfoot motion was significantly affected by footwear only at the 0.32-m height and only for the male data set. The lowest value, which was for the combat boot, differed significantly from the values for the other footwear types, but the values for the jungle boot and the Red Wing work boot were also among the lowest.

Considering the overall findings for the jump/landings, it appears that the combat and the jungle boots did not absorb vertical ground reaction forces as effectively as some of the other footwear tested did, particularly the Reebok Pump and the Nike cross trainer. However, there was no evidence in the knee angle data that the body compensated for the large magnitudes of the vertical forces associated with the military boots by increasing the extent of knee flexion. As was found during the locomotor activities, the military boots and the Red Wing work boot were associated with less flexion at the ankle joint compared with some of the other footwear items, but the extent of ankle flexion did not vary in an ordered fashion with the height of the upper. The locomotor activities revealed a greater range of movement at the metatarsal joint with the military boots and the Red Wing work boot than with the other footwear. During the jump/landings, the female data, but not the male, revealed a greater amount of metatarsal flexion with the jungle boot and the Red Wing work boot, compared with the combat boot and the remaining footwear types. The female data also provided some evidence that there was less movement of the calcaneus relative to the lower leg with the military boots and the Red Wing work boot.

Agility Course Run

Results

A summary of the analysis of the male data for time to complete the agility run is presented in Table H-1. A summary of the findings for the women is presented in Table H-2.

There were no significant interactions in either the male or the female analyses, nor was there a significant main effect of fitness. Load was found to be significant in the female analyses, with the time for the 50-lb load being slower than the time for the no-load condition. Load was also a significant main effect in the analysis of the male data. Time increased significantly with each increase in load.

Footwear had a significant main effect on both the male and the female data. For the men, the fastest course completion times occurred with the Reebok Pump and the Nike cross trainer. The values for these footwear types did not differ from each other, but they were significantly different from the values for the remaining footwear. No other significant differences were obtained. For the women, the fastest times occurred with the Reebok Pump, the Nike cross trainer, and the Rockport hiking boot. The times for these footwear items did not differ from each other, but they were significantly different from the times for the remaining footwear types. No other differences were significant.

Discussion

As the name implies, the agility course run required rapid changes in direction and in pace. Unlike the other activities performed in this study, there was only one dependent measure recorded on the task, time to complete the course. Both the men and the women completed the agility run most quickly when wearing the Nike cross trainer. The longest times occurred when the military boots or the Red Wing work boot were used.

Given the layout and demands of the agility course, it is possible that physical characteristics of the footwear, such as mass and outsole friction, may have affected course completion times. The Nike cross trainer was the lightest item tested; the military boots and the Red Wing work boot were the heaviest. However, neither the men's nor the women's course times increased in an ordered fashion with boot mass. Hamill and Bensel (1992) tested the frictional characteristics of the outsoles of the footwear on a number of different surfaces. It was found that the combat and the jungle boots had relatively low coefficients of friction on dry surfaces compared with the Nike cross trainer. However, again neither the men's nor the women's course completion times varied in an ordered manner with the results of the testing of the coefficients of friction.

Robinson et al. (1986) found that times to complete an agility course identical to the one used in this study decreased with decreases in range of motion at the ankle. They maintained that the restriction in normal ankle motion inhibited the leg from obtaining positions of mechanical advantage, thereby decreasing one's ability to make directional changes requiring a large horizontal force component and increasing time to course completion. In the present study, the three longest times were associated with the three footwear items with the highest uppers. Analyses of the sagittal plane kinematics for walking, marching, and running revealed that the smallest maximum ankle dorsiflexion angles occurred when the military boots or the Red Wing work boot were used. Thus, there is evidence from the sagittal plane kinematics for the locomotor movements that these three types of footwear restricted ankle motion to a greater extent than the other items tested did. Furthermore, although the locomotor movements did not yield identical findings for the antero-posterior component of ground reaction force, there was evidence during walking and marching that the times to maximum braking force were relatively long when the military boots and the Red Wing work boot were used and relatively short when the Nike cross trainer was worn. It is possible that the differences among the footwear items in time to maximum braking force were also a factor affecting performance on the agility course.

GENERAL DISCUSSION

In this report, the fitness and the load variables have been treated only in those instances in which they interacted with footwear to affect performance. However, it is appropriate to discuss, at least briefly, the influence of these other factors before discussing the study findings related to footwear as they impact development efforts in the area of future military boots.

Fitness Level and Load

Few of the analyses of the dependent measures yielded a significant main effect of fitness. The significant differences among fitness groups were essentially limited to electromyographic responses during marching and the 0.72-m jump/landing. Furthermore, the few significant effects did not reveal consistent relationships among fitness levels.

On the locomotor movements and, to a lesser extent, on the jump/landings, fitness interacted with load to significantly affect many of the parameters of ground reaction force and sagittal plane kinematics. Assignment to a fitness group was based solely on aerobic capacity and groups were not matched on physical characteristics, such as height, body mass, or percentage of body fat. It is possible that differences among fitness groups in these physical characteristics differentially affected performance under the various load conditions to yield the significant interactions. Regardless of the possible reasons underlying the significant findings related to interactions of fitness and load, the results of this study suggest that, to better understand load-carrying behavior, future research should include investigation of the influence that the physical characteristics of the load-carrier may have on kinetic and kinematic measures.

In addition to interacting with fitness to affect locomotor and jump/landing performance, load had a significant main effect on many of the dependent variables. Oxygen consumption and heart rate during the locomotor movements generally increased with increases in load weight, as would be expected from past research (Gordon et al., 1983; Pierrynowski, Winter, and Norman, 1981; Soule et al., 1978). During walking and marching, but not during running, first maximum forces of the vertical ground reaction force component increased with load; second maximum vertical force increased with load during all three locomotor movements, as did average vertical force and total vertical impulse. With regard to the antero-posterior ground reaction force component, the magnitudes of both maximum braking and maximum propelling forces increased with load.

In an analysis of the effects of load on body kinematics during walking, Kinoshita (1985) found increased knee flexion as load was increased. In this study as well, maximum knee flexion during walking and marching increased with load, although the effect was not significant. However, a number of kinematic measures recorded during the locomotor movements did yield a significant main effect of load, including maximum ankle plantarflexion, maximum ankle dorsiflexion, and maximum metatarsal flexion. There were, as well, several categories of dependent measures that revealed few, if any, load effects. These were the in-shoe pressure, rearfoot movement, and electromyographic parameters.

Footwear

The military boots included in the materials testing phase (Hamill and Bensel, 1992) and in the present human user testing phase of this research were developed to meet many requirements. In addition to the goals of enhancing the mobility of the wearer and minimizing the occurrence of lower extremity injury during performance of a wide variety of activities on a wide range of surfaces and terrains, cost, storage life, and a myriad other factors influenced the decisions that led to the versions of the combat and the jungle boots used in this research. The decisions included trade-offs, where some factors were sacrificed for others. No doubt, it can also be said that the design of the commercial items tested here emanated from consideration of many factors in addition to the performance efficiency and lower extremity health of the wearer, although the factors may have been different from those influencing military boot development. It is likely that these decisions also included trade-offs in arriving at the finished item. Thus, as is the case for the military footwear, the commercial items do not represent the "ideal" footwear. Furthermore, the commercial footwear items are not appropriate for use as military field boots. However, as Hamill and Bensel pointed out in the context of the materials testing of the military and the commercial footwear, the commercial items can be viewed as "models" against which to assess the characteristics of the military boots.

In comparing the performance of the footwear items included in this human user testing phase of the research, there are findings that differentiate the combat and the jungle boots from one or more of the commercial items and that have implications for development of future generations of military footwear. Some of the findings relate to differences among footwear items for the vertical ground reaction force component.

During marching, use of the combat and the jungle boots resulted in the highest impact peak forces. The military boots were also associated with high impact forces during the jump/landings. During walking and marching, the magnitudes of second maximum vertical force, the thrust or propulsive peak, were relatively large for the combat and the jungle boots, especially when compared with the magnitudes for the Reebok Pump and the Nike cross trainer. These results, along with the high values of peak g for the military boots obtained by Hamill and Bensel (1992) on the impact test, suggest that means to improve shock attenuation in both the heel and the forefoot areas be addressed in design of future military footwear.

Unlike the results for walking, marching, and the jump/landings, the magnitudes of the vertical ground reaction force peaks during running were either essentially the same for all footwear types or were lower for the military boots than for some of the commercial items. Furthermore, there was no evidence during running of differences among footwear types in the extent of maximum knee flexion, a kinematic adjustment that Clarke, Frederick, and Cooper (1983) reported in association with differences in shoe midsole hardness. In addition, the military boots resulted in relatively small rearfoot angles at foot strike during running, whereas Nigg et al. (1987) found larger rearfoot angles at foot strike with harder midsole material and maintained that this adjustment served as a protective mechanism for controlling application of external ground reaction forces to the foot.

In light of the high vertical ground reaction forces for the military boots during walking, marching, and the jump/landings, and the lack of evidence of kinematic adjustments at foot strike during running in the military boots, the findings for running raise the possibility that the vertical ground reaction forces were transmitted to the skeletal system essentially unattenuated when the military boots were used. This possibility further emphasizes that improved shock attenuation should be addressed in future military footwear. In addition, the men's fastest times to first maximum force during running occurred with the combat and the jungle boots and the women's fastest times occurred with the combat boot. These findings are compatible with the materials testing in which Hamill and Bensel (1992) found that the shortest times to peak g on the impact test were associated with the military boots. The results again suggest the need for improving the shock attenuating characteristics of the military footwear.

Arrays of pressure transducers were placed in the footwear tested in this study to augment the ground reaction force data with assessments of pressure distributions at the shoe/foot interface. Peak pressure measured on the impact test revealed substantial differences between the military boots and the Nike cross trainer, as well as some of the other commercial items (Hamill and Bensel, 1992). Thus, it was expected that the in-shoe pressure transducers would reveal higher peak pressures with the combat and the jungle boots than with some of the commercial items during performance of the locomotor activities and the jump/landings. However, only one analysis yielded a significant effect of footwear on peak heel or forefoot pressures. This was the analysis of the female data for peak heel pressure during running, which revealed significantly lower pressure with the Reebok Pump than with any of the other footwear tested.

It is remarkable that more extensive differences among footwear types were not obtained, but it is even more remarkable that peak pressures were rarely affected significantly by the loads carried by the participants, given that the pressure measurement device was calibrated to the participant's body mass, not body mass plus load mass. Although it is possible that peak pressures are not sensitive to variations in footwear type or load, it is also possible that the pressure measurement devices used in this study did not function as intended. Determinations of the sensitivity of the device to footwear and load manipulations must await future testing.

The physiological measures of oxygen uptake and heart rate recorded in this study during treadmill walking, marching, and running were, like peak in-shoe pressures, variables that would be expected to differentiate among footwear types, given Hamill and Bensel's (1992) findings from the physical testing of the impact properties of the footwear. Hamill and Bensel reported that the combat and the jungle boots have low coefficients of restitution at both the heel and the forefoot areas, particularly when compared with the Nike cross trainer. Thus, higher levels of energy expenditure would be expected with the military boots. Furthermore, the combat and the jungle boots were the heaviest footwear items tested, which should also increase energy expenditure relative to lighter footwear types (Jones et al., 1984; Jones et al., 1986; Martin, 1985).

The effects of footwear on the physiological measures recorded in this study were limited. Heart rates of the men and the women did not vary significantly as a function of footwear during any of the locomotor activities, neither did the men's oxygen consumption. Footwear did have a significant effect on the women's oxygen uptake during walking and running. However, oxygen uptake did not increase in an ordered fashion with increases in footwear mass. The highest uptake levels during both walking and running occurred with the Red Wing work boot, although the masses of the leather and the jungle boots are greater than that of the Red Wing work boot by 0.36 kg and 0.51 kg, respectively. In addition, oxygen consumption did not increase with decreases in coefficient of restitution. Both the combat and the jungle boots have lower coefficients than the Red Wing work boot does. Also, oxygen uptake did not appear to be dependent upon shoe hardness, as Frederick (1984, 1986) reported, given that the durometer readings for hardness on the Shore A scale were essentially equal for the combat boots and the Red Wing work boot.

In past studies of changes in energy expenditure as a function of footwear mass, mass was varied while other characteristics were held constant (Jones et al., 1984; Martin, 1985) or only two footwear types, differing in both mass and design features were compared (Jones et al., 1984, 1986). Likewise, in Frederick's (1984, 1986) research on variations in shoe hardness as related to energy expenditure, mass was held constant. In the present research, six footwear items were contrasted and they varied in many characteristics, in addition to mass and hardness. The extensive variations among footwear items may account for the fact that there were only a few instances in which footwear had a significant effect on the physiological measures. It may also account for the fact that, in the few instances in which a significant effect was obtained, the findings were at odds with those from past studies.

It has already been suggested that, in future military footwear, improvements be made in shock attenuation characteristics. Differences among the footwear items tested in this research that are related to metatarsal angle measurements raise another area to consider in future footwear development. During walking, marching, and running, use of the military boots and the Red Wing work boot resulted in the greatest degrees of metatarsal flexion, whereas use of the Reebok Pump generally yielded the lowest values for metatarsal flexion. The flexion velocities for the combat boot and the jungle boots were also quite high. The results for the military boots describe an extreme and rapid raising of the heel by movement about the metatarsal-phalengeal joints. This action, performed in a repetitive manner during locomotion, could strain the long plantar ligaments extending from the heel to the ball of the foot, precipitating the onset of plantar fasciitis.

In measuring forefoot flexibility during the materials testing phase of this research, Hamill and Bensel (1992) found the Red Wing work boot to be the least flexible of the items tested, followed by the combat and the jungle boots, with the Reebok Pump being very flexible. It may be because of stiffness of the forefoot that the military boots and the Red Wing work boot required a relatively great degree of metatarsal flexion to accomplish toe-off and propel the body forward into the next step, particularly when compared with the Reebok Pump. If indeed stiffness in the forefoot of a footwear item affects the wearer's metatarsal flexion angle during locomotion, the findings from this study suggest that means to improve forefoot flexibility be addressed in design of future military footwear.

Cavanagh (1980) maintained that the less flexible the footwear, the more the lower extremity muscles would be stressed. Given the materials testing results indicating that the military boots and the Red Wing work boot were stiffer than the other footwear types (Hamill and Bensel, 1992), it was expected that differences in muscle activity levels as a function of footwear type would be revealed in the present study. However, there was only one analysis in which footwear had a significant effect on signal amplitude of a muscle group, the male data for the anterior tibialis collected during running. Arsenault et al. (1986) reported that patterns of muscle activity, although extremely stable within individuals, may vary extensively across individuals. Thus, the pooling of the participants' data in the present study may have obscured any inter-individual footwear effects on muscle activity levels.

Results from the present study pertaining to rearfoot motion parameters have implications for development of future military boots. Excessive subtalar joint pronation has been linked to lower extremity injury (Hlavac, 1977; James et al., 1978). However, pronation is a mechanism for decreasing the forces transmitted to the body following foot strike (Clarke, Frederick, and Hamill, 1983; Nigg et al., 1986). Thus, it appears that some intermediate level of stability would be desirable in a footwear item.

In those instances in the present study in which footwear had a significant effect on rearfoot angles during ground contact, the military boots tended to be associated with the smaller angles, indicating less movement of the calcaneus relative to the lower leg, than some of the other footwear types tested. This was the case in the male and the female data for rearfoot angle at foot strike during running, as well as total rearfoot motion during running. Furthermore, in assessing rearfoot stability during the materials testing phase of this research, Hamill and Bensel (1992) found the combat and the jungle boots to be highly stable at both the medial and the lateral borders of the heel. Both the human user data and the materials testing data, therefore, suggest that, in design of future military footwear, no action be taken that would increase rearfoot stability. The data further indicate that design changes that may indirectly result in somewhat decreased rearfoot stability, such as selection of softer midsole materials (Clarke, Frederick, and Cooper, 1983), would not be likely to compromise the stability of the military boots.

Some of the results of the present study have implications for another aspect of future military boots, the design of the upper. All of the footwear tested extended to at least the level of the lateral malleolus, but there was a difference of almost 14 cm between the item with the highest upper, the combat boot, and the item with the lowest upper, the Nike cross trainer. After the combat boot, the jungle boot, followed by the Red Wing work boot, had the highest upper. The longest times to complete the agility course run were recorded with these three footwear items. The course demanded rapid changes in direction and in pace. It appears that the high uppers may have restricted ankle motion, thereby increasing course completion times.

The analyses of sagittal plane kinematics during walking, marching, and running provided evidence that the military boots and the Red Wing work boot restricted ankle movement to a greater extent than the other footwear tested. The ankle angle data collected during the locomotor movements revealed that the smallest maximum dorsiflexion angles and the greatest negative magnitudes of dorsiflexion velocity were generally associated with the military boots and the Red Wing work boot, the three footwear types having the highest uppers. These findings for the military boots and the Red Wing work boot during locomotion describe a limited and rapid ankle dorsiflexion.

The ankle angle data recorded during the jump/landings also revealed that use of the military boots and the Red Wing work boot generally resulted the smallest maximum dorsiflexion angles. However, the lowest dorsiflexion velocities were achieved with these footwear items. In a study of sagittal plane kinematics during jump/landings, McNitt-Gray (1991) found that the ankle joint, as well as the hip and knee joints, was in an extended position at touchdown. McNitt-Gray maintained that this posture provides the potential for the full range of joint motion to be used to minimize the load imposed on the skeletal system during landing. Thus, the participants in this study may have been exposed to more substantial loads on the body during jumping in the military boots and the Red Wing work boot because of constrained ankle movement. Limited dorsiflexion may also have resulted in greater loads being transmitted to the body during walking, marching, and running in the military boots and the Red Wing work boot. These findings, together with the longer times on the agility course when these footwear items were used, suggest that efforts addressing future military footwear consider whether the upper heights of the present boots are optimal in terms of ankle mobility and protection of the musculoskeletal system from impact loads.

SUMMARY AND CONCLUSIONS

This report contains the findings from the second phase of a two-phase research program to gather information about the biomechanical properties of current military boots. In the first phase (Hamill and Bensel, 1992), the combat and the jungle boots were subjected to materials testing, along with six types of commercial sport and work shoes. The second phase was an analysis of the functioning of men and women wearing the same types of military boots and four of the commercial footwear items used in the first phase. A principal objective of this research was to develop, from the data acquired, a series of recommendations for future military footwear with regard to design, materials, and other features that would benefit the performance and the lower extremity health of military personnel. A number of recommendations have been formulated on the basis of the outcome of the materials and the human user testing. The recommendations and suggestions for their implementation in future military footwear are presented in a separate report (Hamill and Bensel, 1996).

The commercial footwear items analyzed in this research program were not developed to meet the extensive requirements that military field boots must fulfill. However, the commercial items were selected because they incorporated material and design concepts that could be adapted to a military boot had this appeared to be advantageous on the basis of the results of the present research program.

The major findings from this study related to differences between performance of the military boots and the commercial footwear items are summarized below.

1. Vertical ground reaction forces recorded during walking, marching, and jump/landings were relatively high when the combat and the jungle boots were used. During running, vertical ground reaction force peaks for the military boots were equal to or less than those for some of the commercial items.

2. Sagittal plane kinematics of the hip and knee joints during walking, marching, running, and jump/landings revealed few differences attributable to the type of footwear being worn. However, ankle dorsiflexion was limited in the military boots in comparison with some of the other footwear types, whereas there were larger and higher velocity angular movements about the metatarsal-phalangeal joints in the military boots.

3. Rearfoot angle at foot strike was smaller and the extent of total rearfoot motion was less during running in the military boots than in some of the commercial footwear. Rearfoot movement parameters recorded during walking, marching, and jump/landings did not reflect consistent differences among the footwear items tested.

4. Times to completion of the agility course run were slower in the military boots than in some of the commercial footwear.

5. In-shoe heel and forefoot pressures, leg muscle activity, and energy expenditure measures were not generally affected by the type of footwear worn.

From the results of the present testing, together with the results of the materials testing phase of this research, it is concluded that a number of areas must be addressed in any future efforts to develop military footwear that would benefit the performance and the lower extremity health of the wearer. These areas are identified below and discussed in detail by Hamill and Bensel (1996).

1. Shock attenuation characteristics in both the heel and the forefoot.

2. Flexibility in the forepart.

3. Stability of the rearfoot.

4. Height of the upper.

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